High Energy Muon Collider:

Is It Right Machine For US?
Are These Guys Serious?
When Will We Know It Is Feasible?

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1 May 2009

with input from:

S.Geer, M.Zisman, A.Tollestrup, A.Bross, Y.Mori, K.Yonehara, A.Skrinsky, A.Jansson, H.Kirk, R.Palmer, Yu.Alexahin, S.Holmes, R.Johnson, D.Kaplan, D.Neuffer, Y.Derbenev, E.Eichten, R.Fernow, V.Lebedev, M.Popovic, J.Norem, M.Lamm, P.Snopok, C.Ankenbrandt, N.Mokhov, D.Summers, J.P.Delahaye, M.Chung, V.Balbekov, A.Zlobin, C.Hill, M.Demarteau… and many others

Big Picture

- LHC is built and will run in 2009:
  - energy frontier moves overseas for next decade(s?)
  - confidence in getting new physics insight ~2012-13
- Growing consensus on the next machine (P5)
  - should be lepton-lepton collider
  - ILC energy reach may not be enough → multi-TeV
  - attention to alternatives (P5 report)
- Alternative schemes:
  - CLIC e+e- linear collider (CDR by ~2010)
  - plasma-wake e+e- linear colliders (emerging)
  - muon collider (aims FSDR by 2013) - advantages

Muon Collider: Small Footprint

Negligible synchrotron radiation

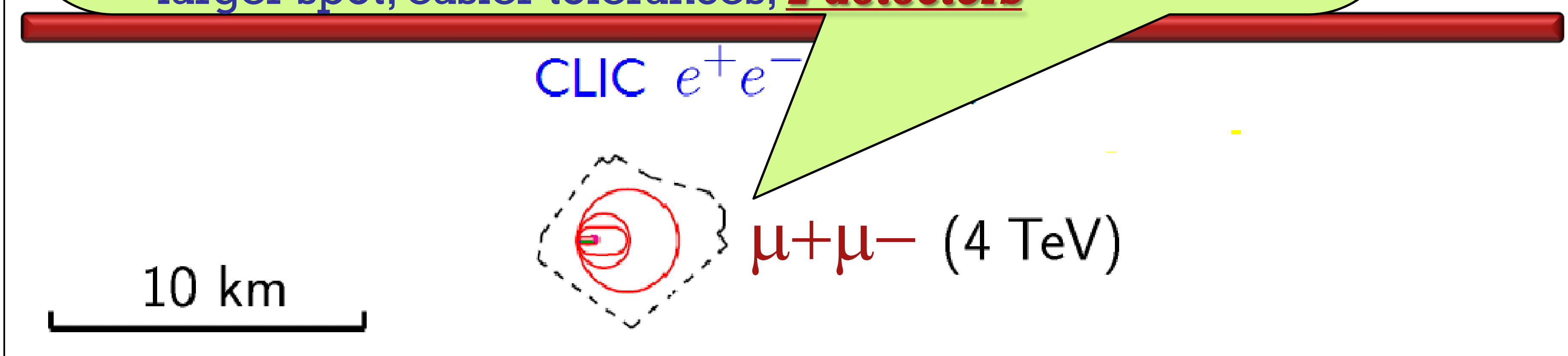
Acceleration in rings rather than linear

Less RF , very high energy reach >4TeV

Collider as a Ring

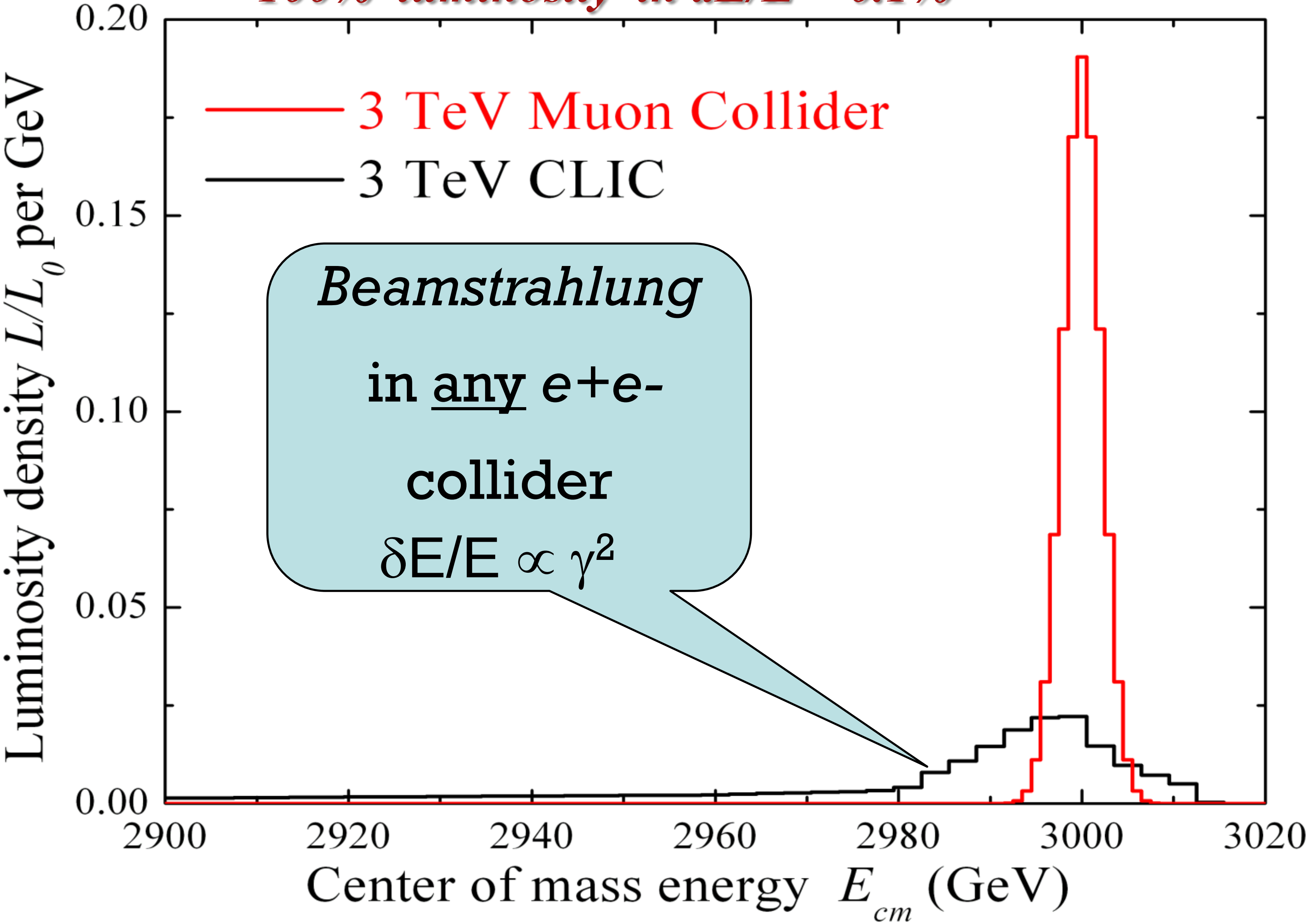
collisions over ~1000 turns of muon lifetime

larger spot, easier tolerances, ***2 detectors***

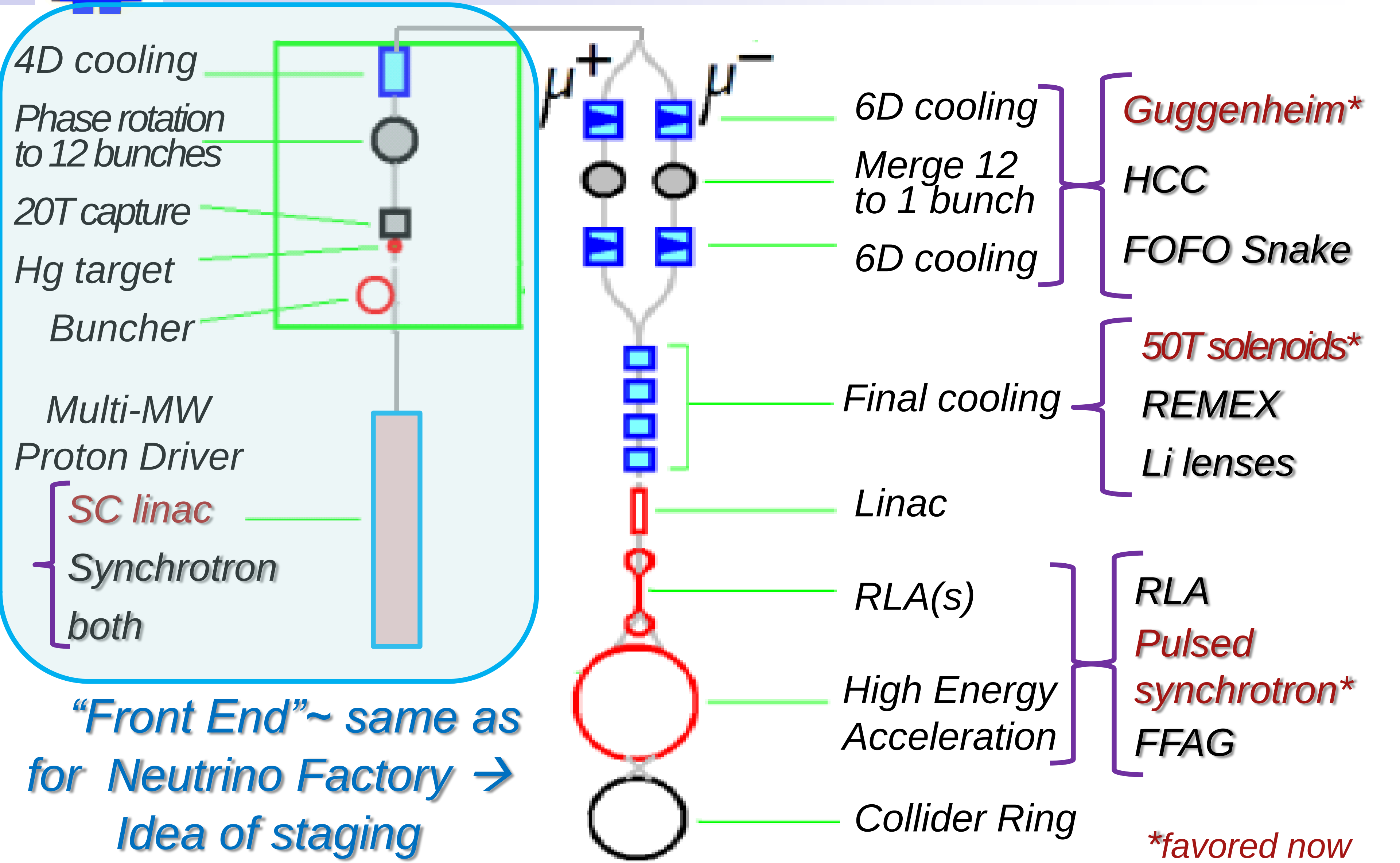


Superb Energy Resolution

100% luminosity in dE/E ~ 0.1%

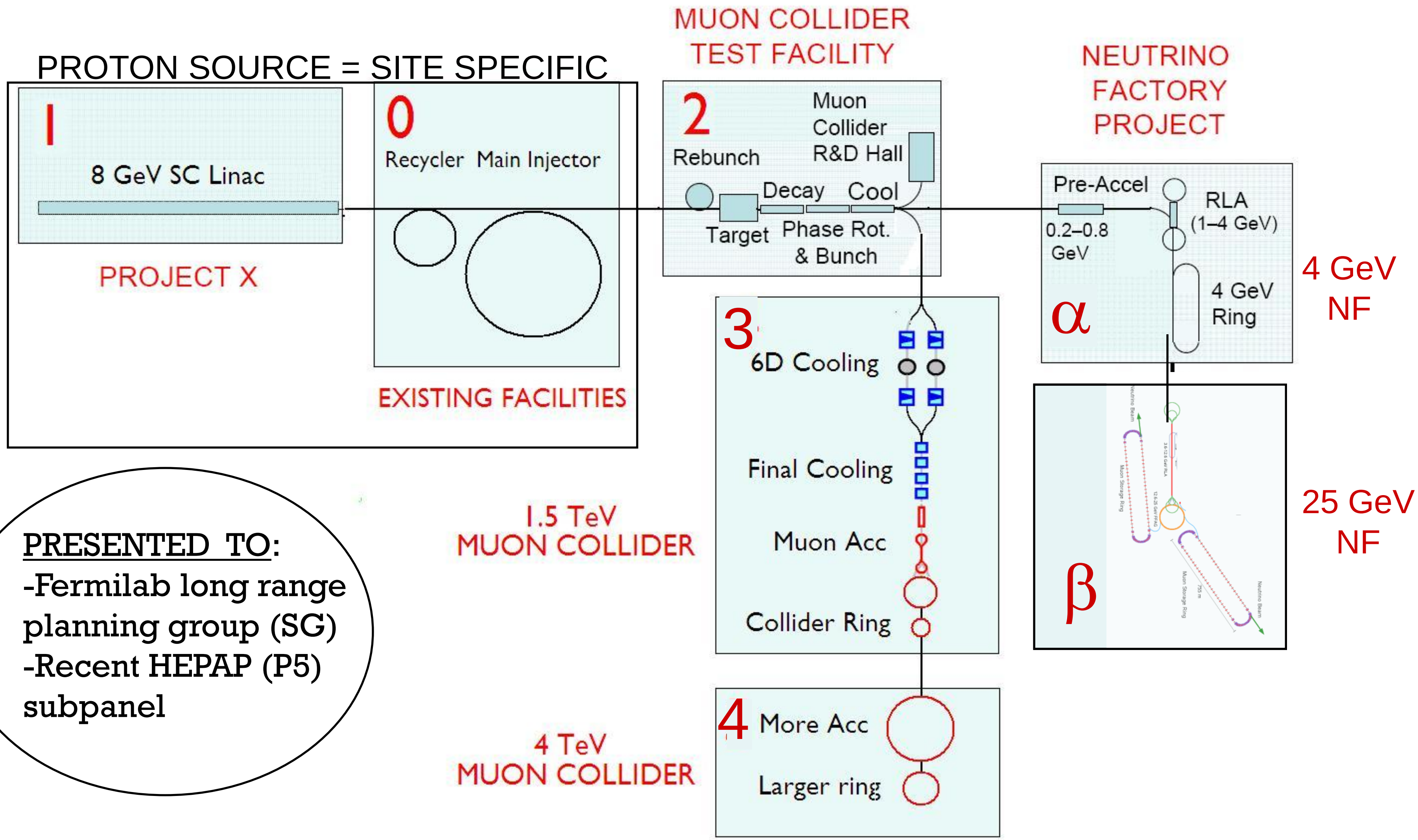


Muon Collider Scheme



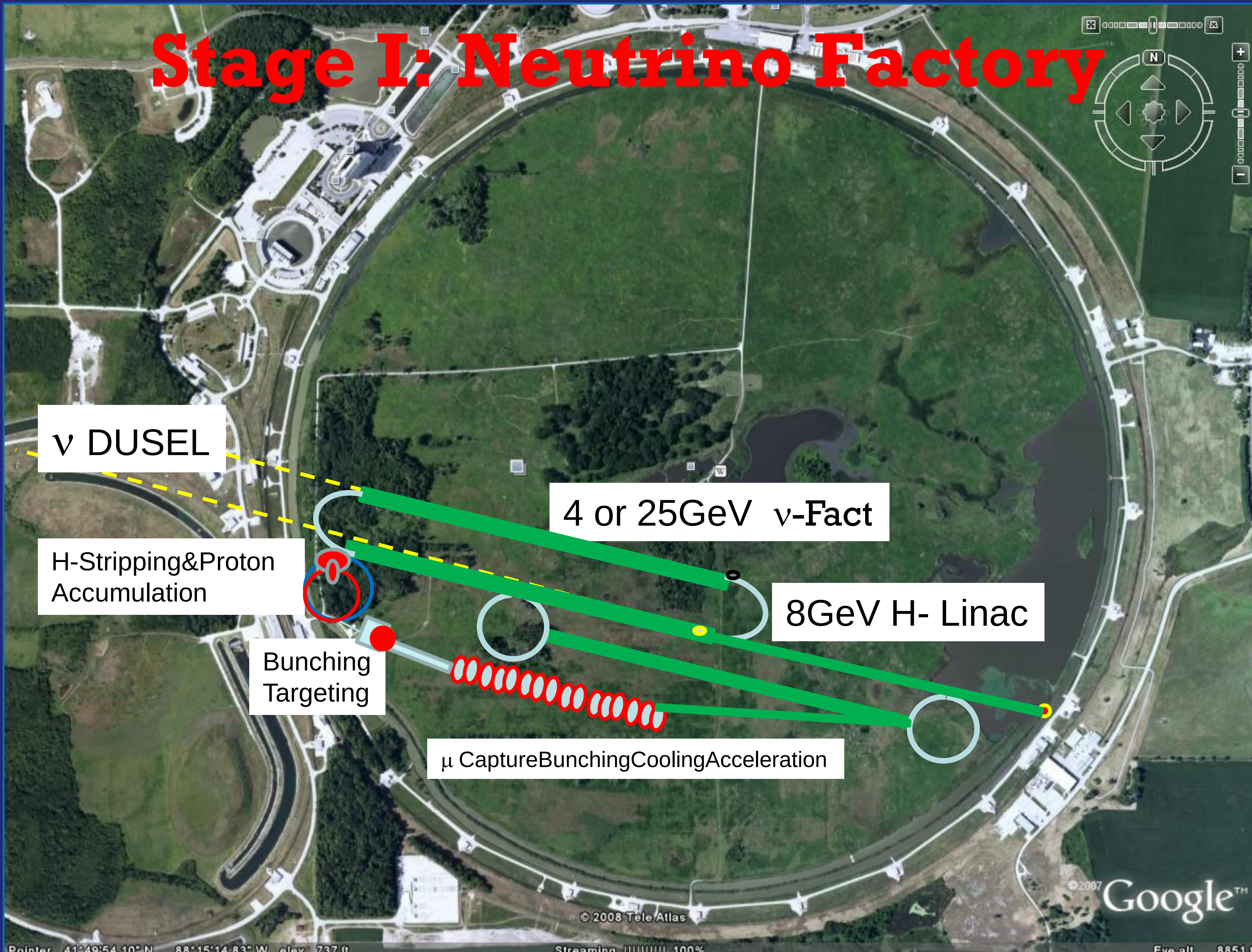
"Front End"~ same as for Neutrino Factory → Idea of staging

FNAL Complex Evolution

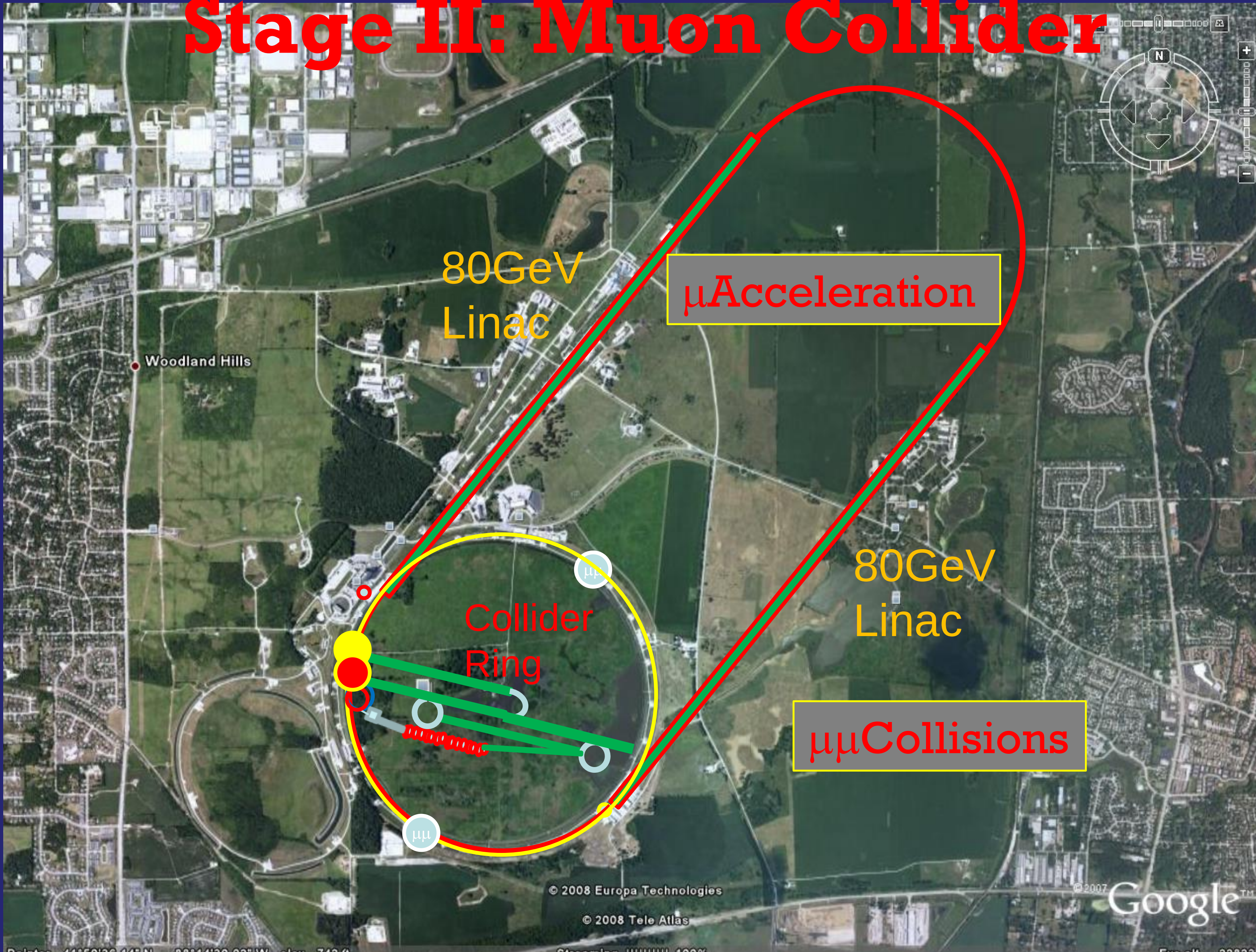


<u>PRESENTED TO</u>:
-Fermilab long range planning group (SG)
-Recent HEPAP (P5) subpanel

Stage I: Neutrino Factory



Stage II: Muon Collider



Muon Collider Parameters

CM Energy	1.5	4	TeV
Luminosity	1	4	10^{34} $cm^{-2}s^{-1}$
Muons/bunch	2	2	10^{12}
Ring circumf.	3	8.1	km
Beta at IP $\beta^* = \sigma_z$	10	3	mm
dp/p (rms)	0.1	0.12	%
Ring depth*	13	135	m
PD Rep rate	12	6	Hz
PD Power	**≈4**	**≈2**	**MW**
Transv.emm. ε_T **	**25**	**25**	**π mm mrad**
Long. emm. ε_L	72,000	72,000	π mm mrad

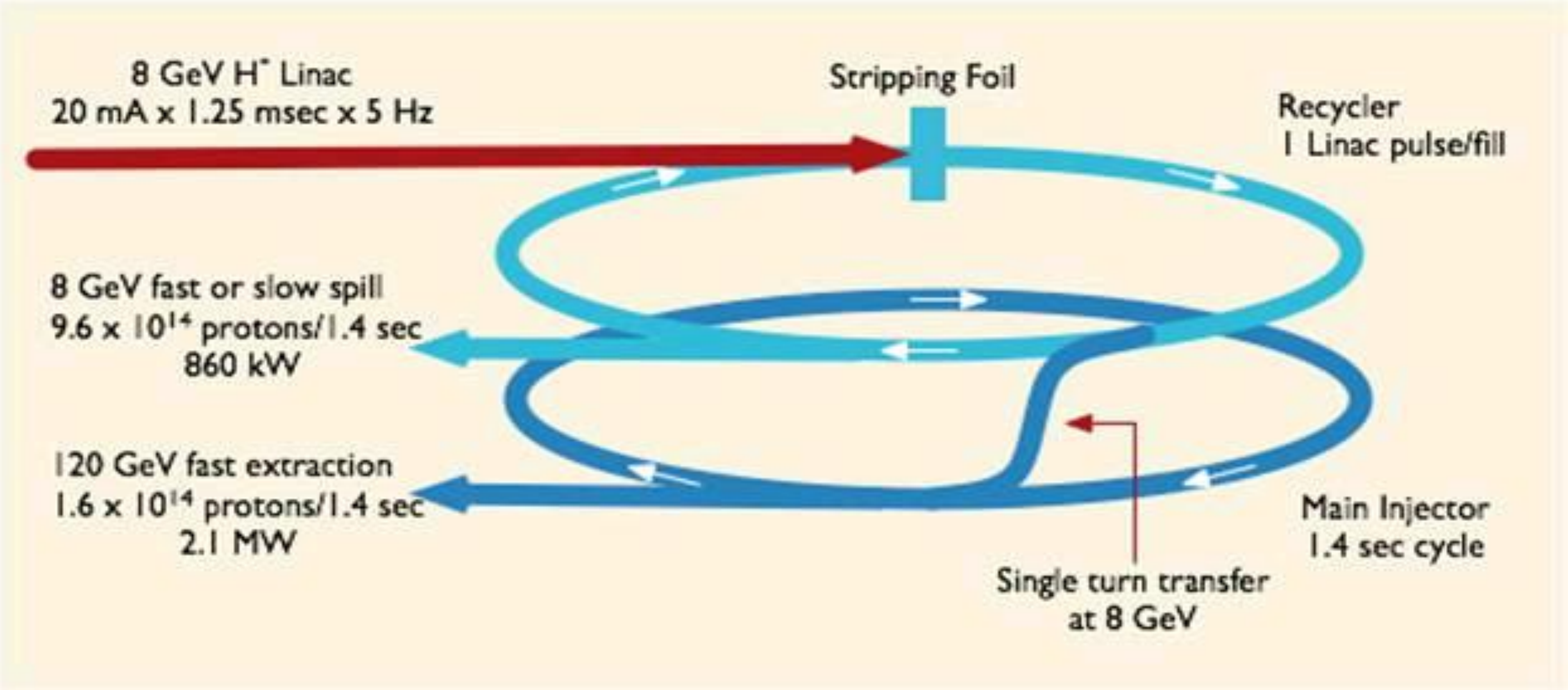
**   depth for ν radiation keeps off site dose <1 mrem/yr*

*** lower emittance option is under consideration (discussion below)*

Main Muon Collider Challenges

- Generate intense short proton bunches
- Convert protons into short muon bunches
- Cool the muons
  - 3 stages : pre- ,main-, final-cooling
- Accelerate muons to 0.75-2 TeV
- Collide (with acceptable background)

Project-X and Muon Complex



- Initial Configuration Document: 1 MW @ 8GeV
- MC/NF need: ~4MW@ different beam structure

Project-X Timeline

- Collaboration is being formed (08-09)
- FNAL Director's Preliminary Cost and Schedule Review (Mar'09)
- Technically limited schedule:

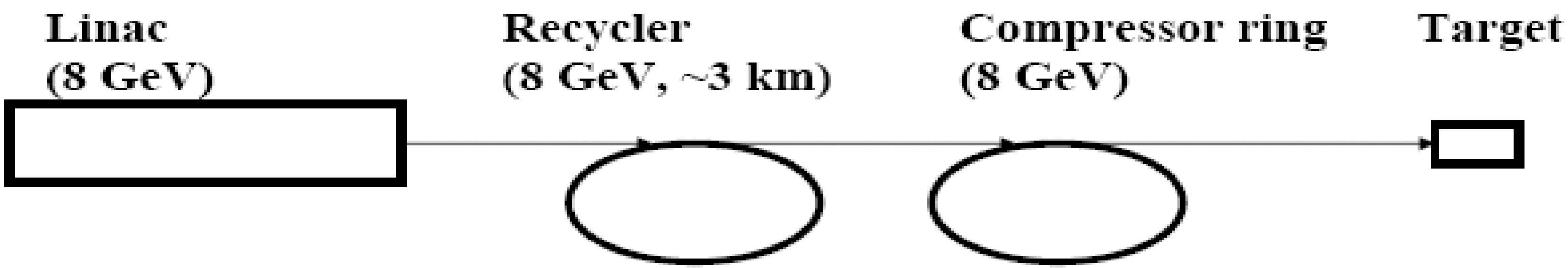
  - CD-0 July 2009
  - CD-1 December 2010
  - CD-2 July 2012
  - CD-3 August 2013
  - CD-4 March 2018

RD&D

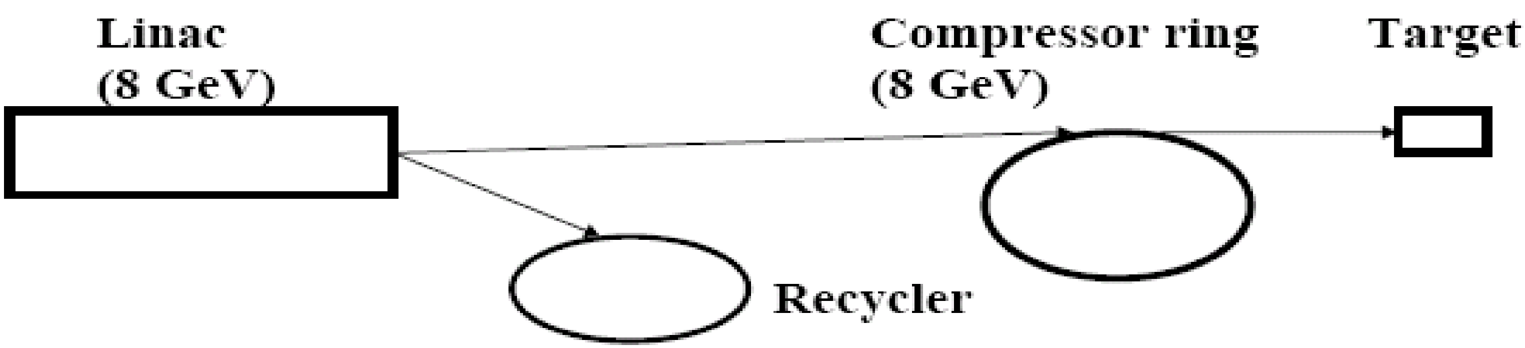
PED

Post-"Project X" : Choices

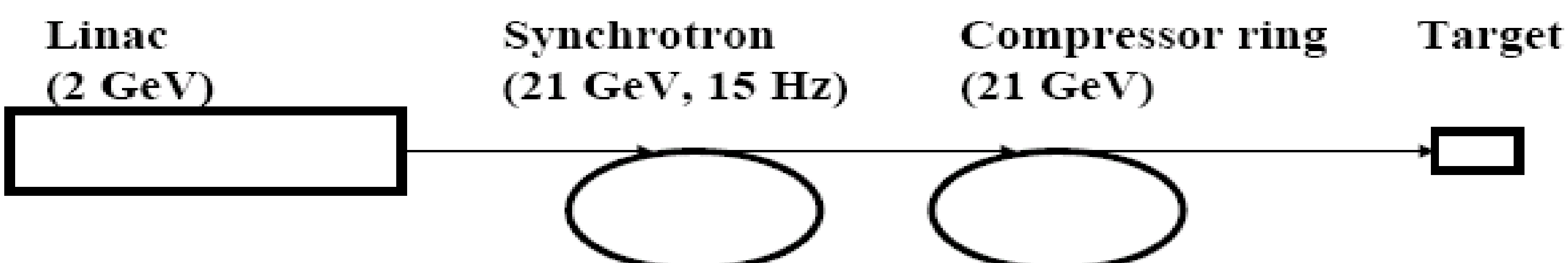
- Present Project-X with injection to Recycler + Compressor ring



- Project-X linac + Compressor ring with direct H^- strip injection



- Alternative Project-X + compressor ring

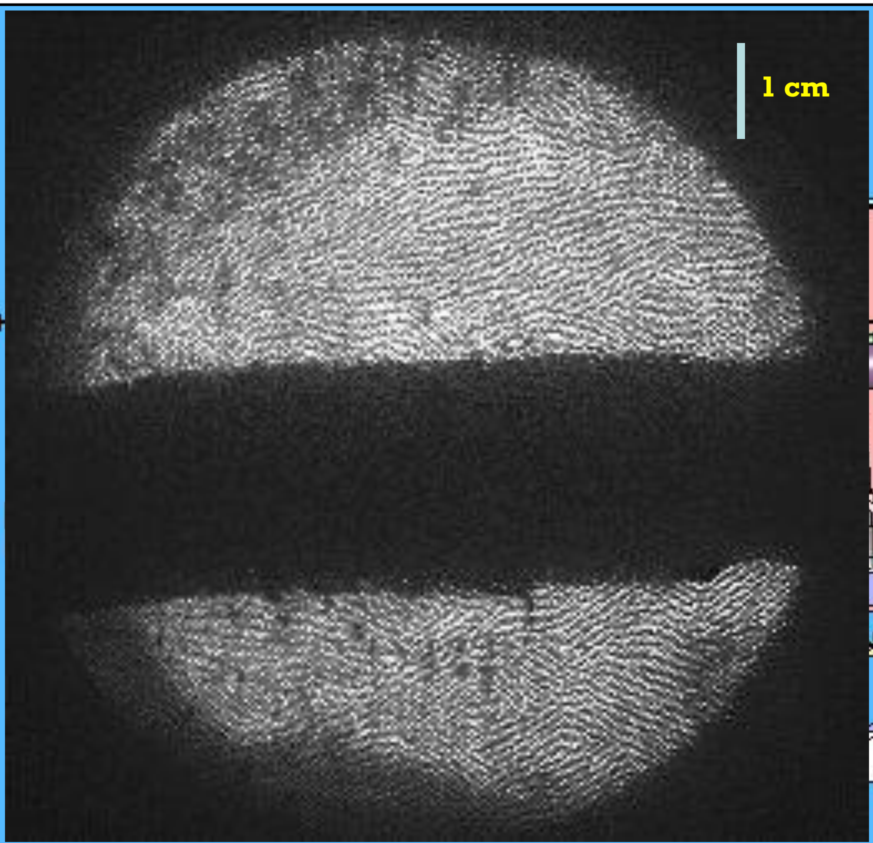


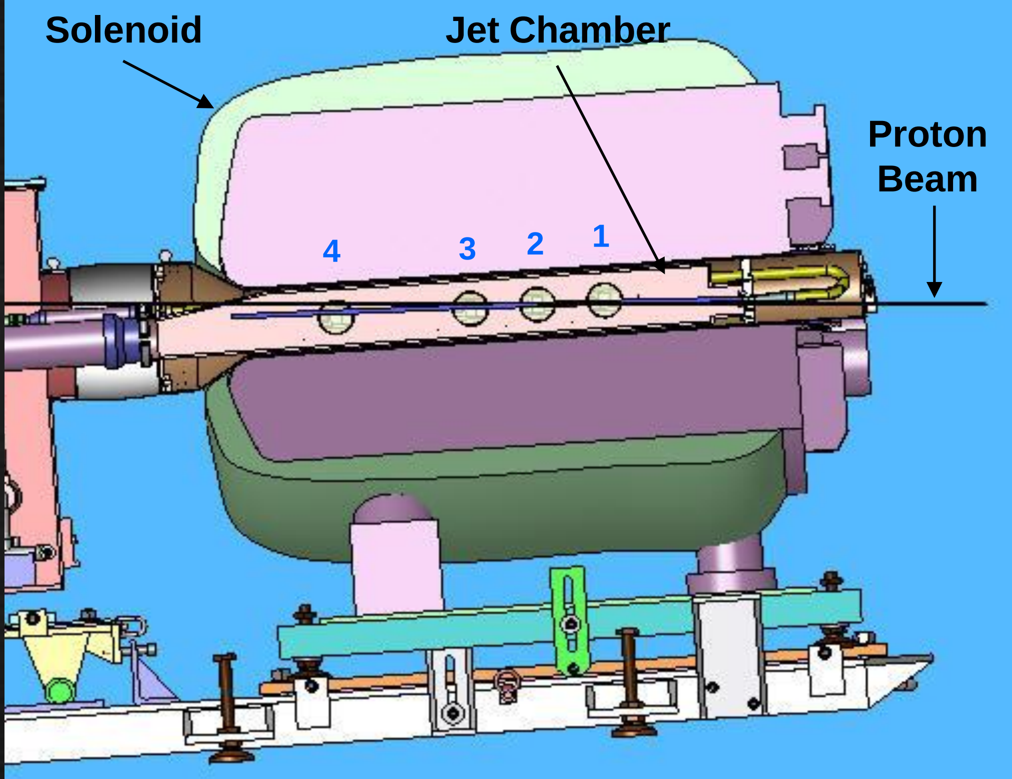
Compressor Ring Issues

- Focusing on the target
- Longitudinal and transverse stability of high Intensity bunches
  - Space-charge
  - Impedance, e-p instability
- Preliminary conclusions:
  - specialized 8 GeV compressor ring feasible for 1 MW in a single bunch mode at 15 Hz
  - further beam power increase possible with either better collection scheme, or bunch merging or with larger energy, (e.g. 21 GeV) ring

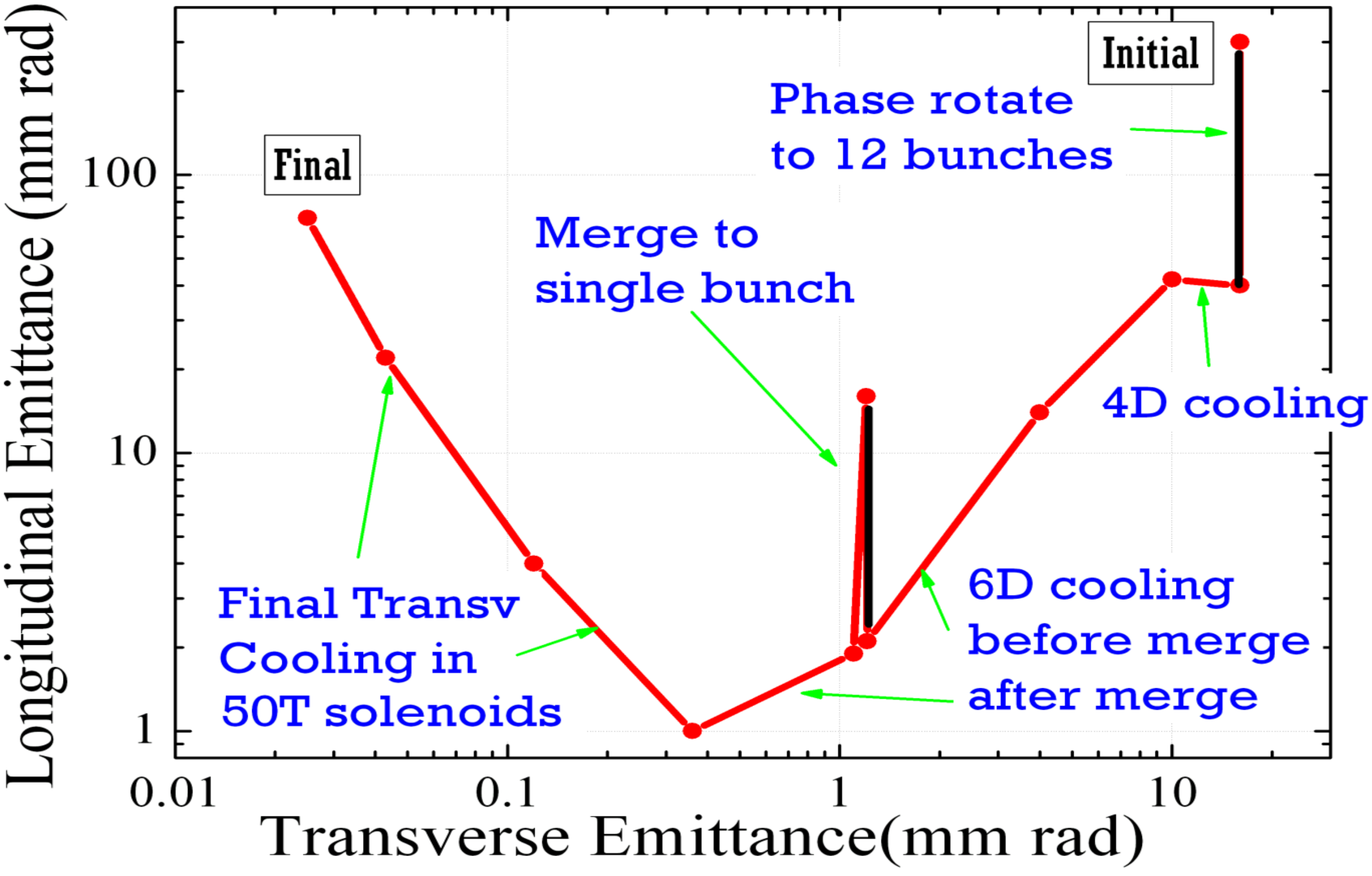
MC/NF Target

- MERIT experiment
  - Demonstration at CERN of 1 cm dia 20 m/s Hg jet target in 15 T & 3e13 24 GeV protons
  - target concept has been validated for 70Hz ~8MW

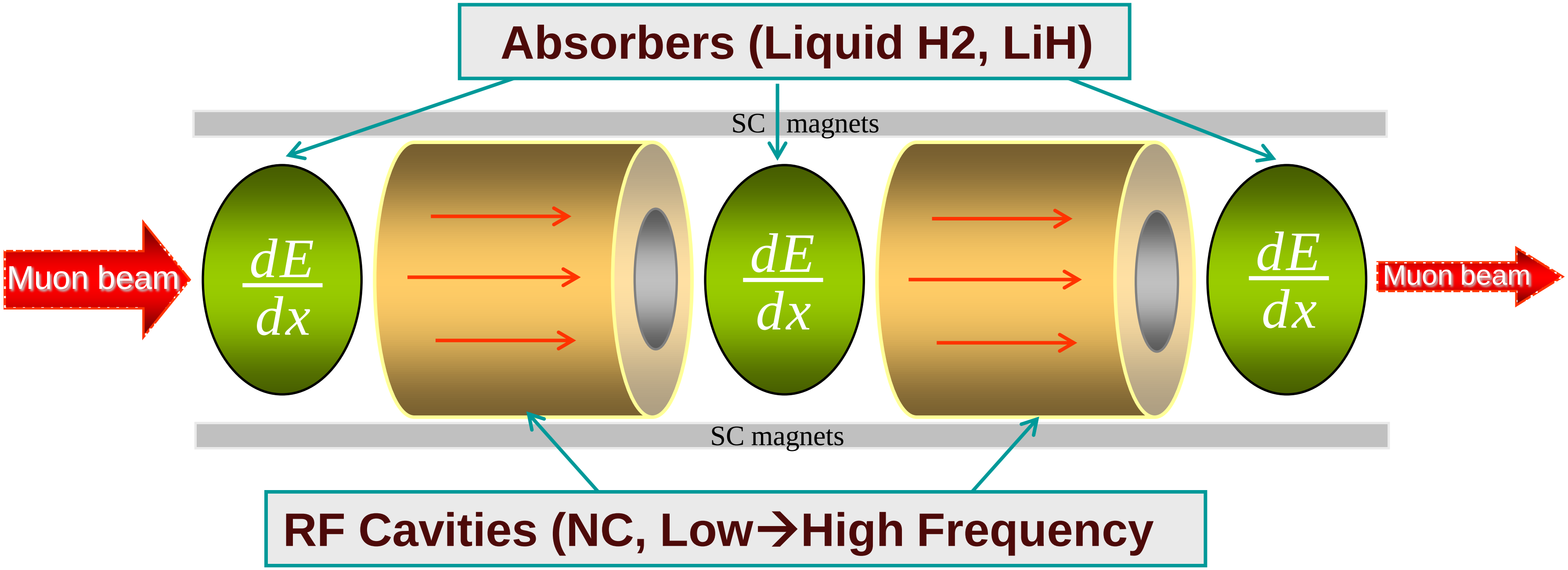




Emittances vs Stage

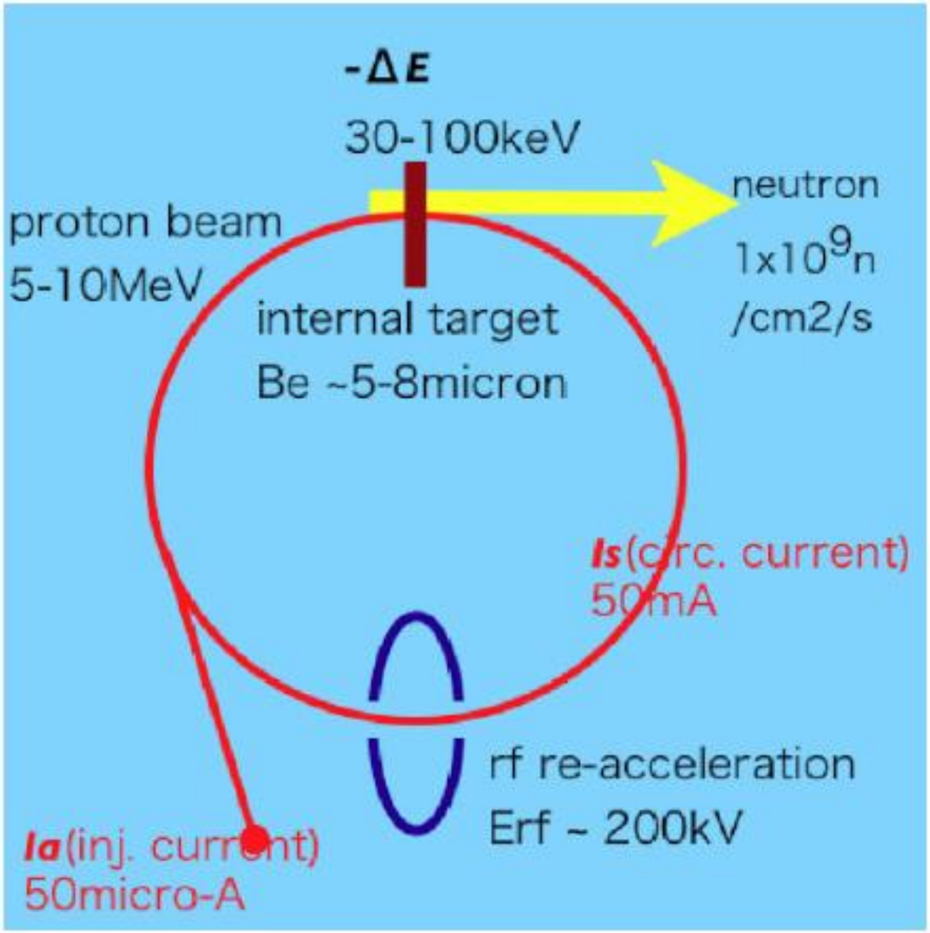


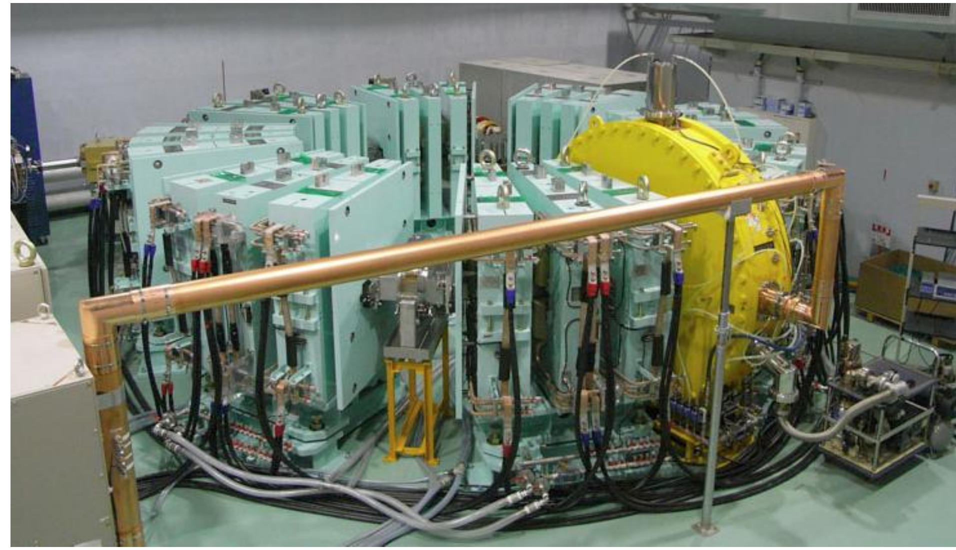
Ionization Cooling is the Key

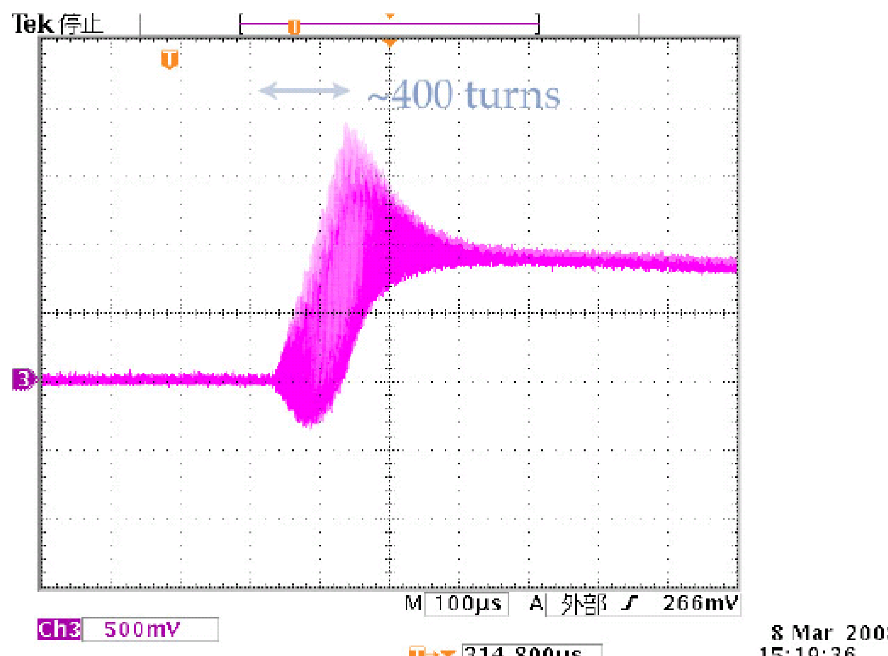


- There is no "mystery" in the ionization cooling
  - single particle physics well understood to simulate
  - seen in low-*E* *p*-rings (Novosibirsk 60's, Osaka ERIT '08)
  - experiment(s) are to address technical challenges

ERIT (Kyoto/Osaka)

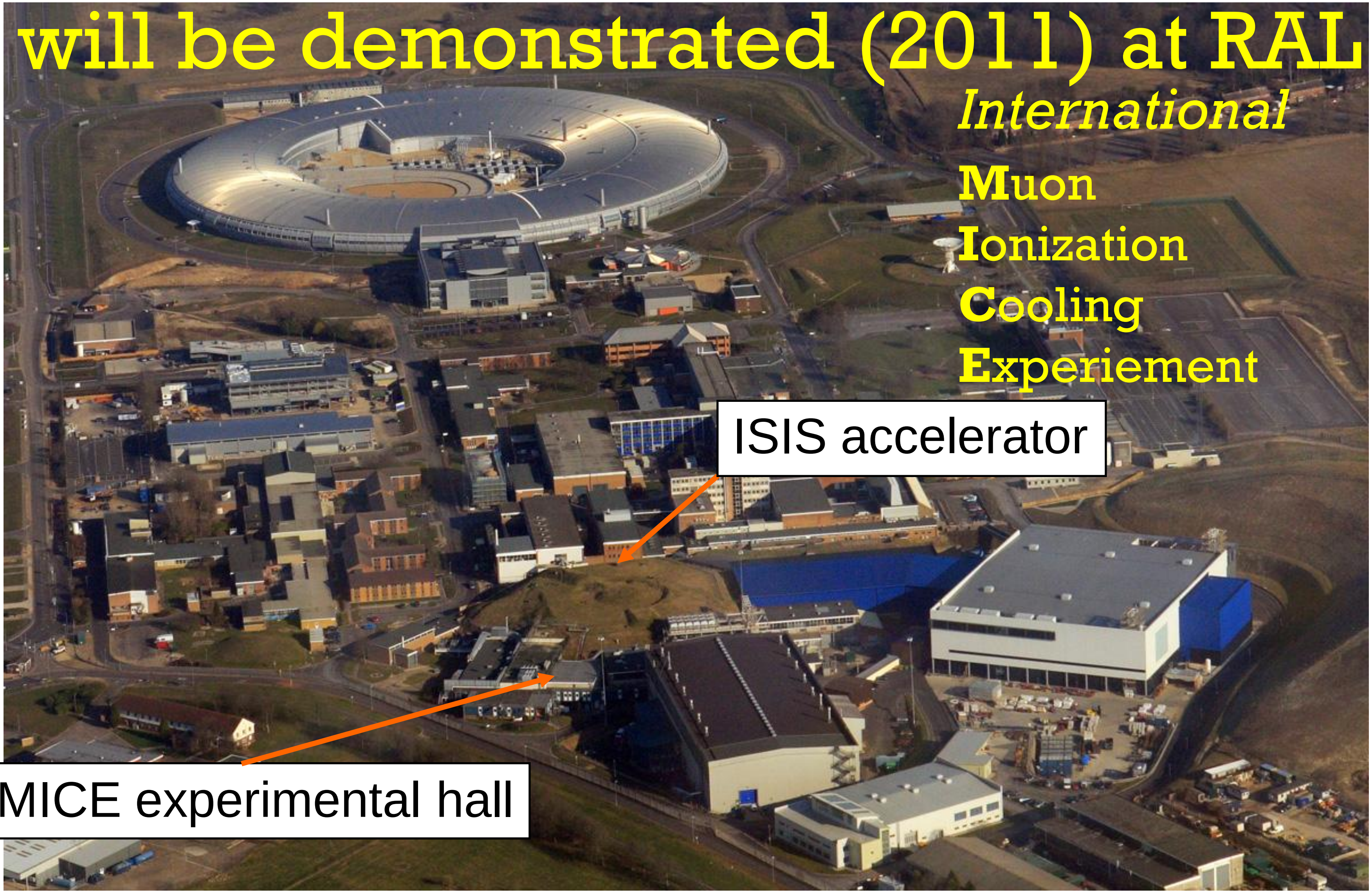






Y.Mori
US PAS Prize '09

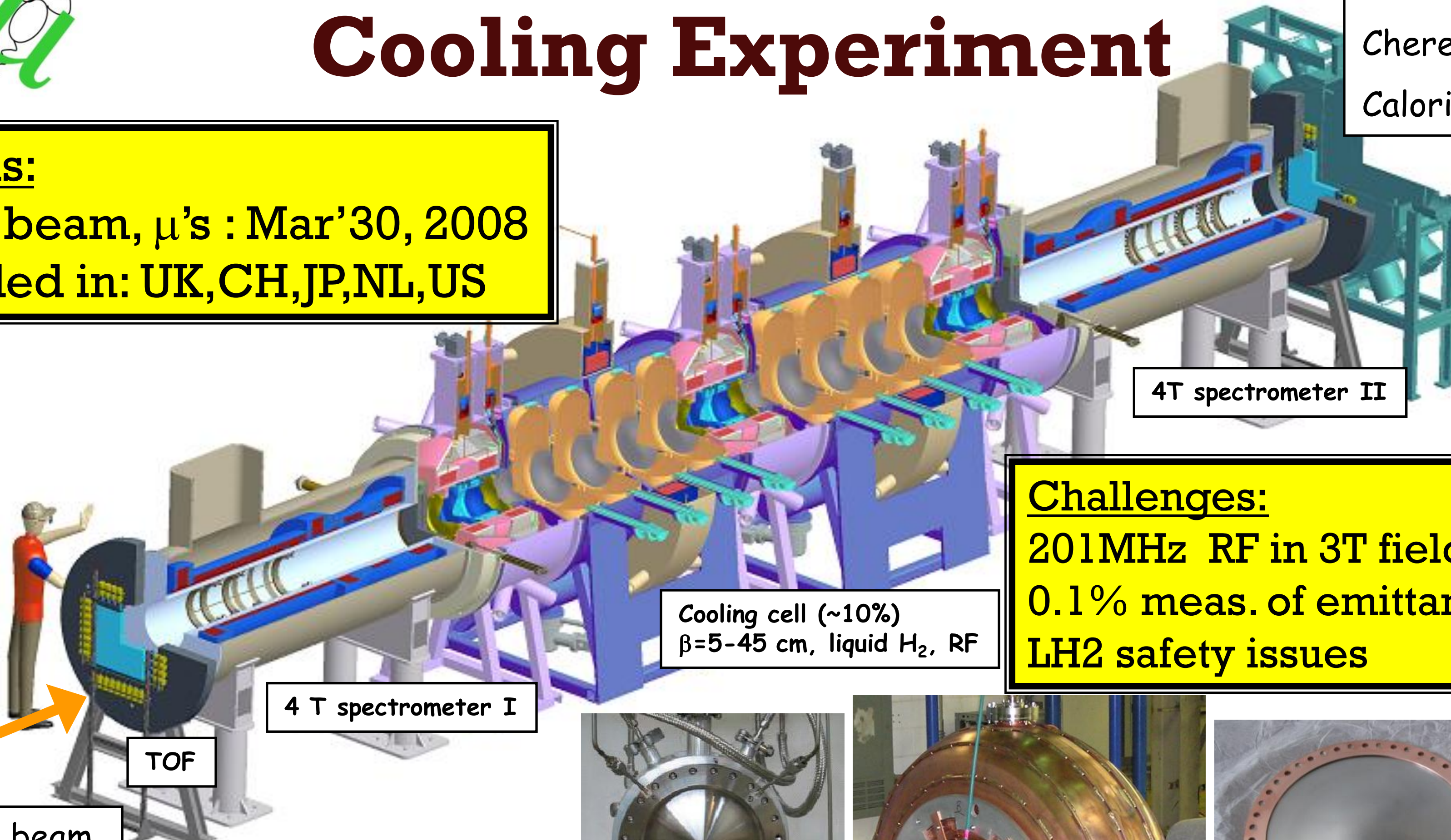
Transverse or 4D-Cooling



Muon Ionization Cooling Experiment

Final PID:
TOF
Cherenkov
Calorimeter

Status:
First beam, μ's : Mar'30, 2008
Funded in: UK,CH,JP,NL,US



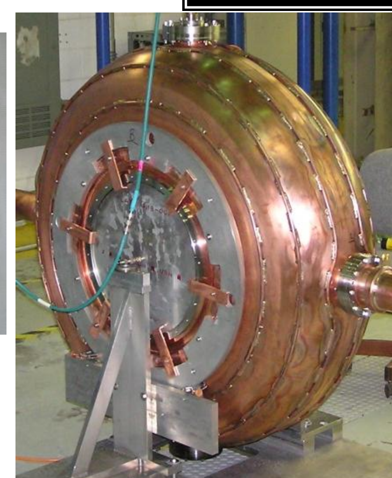
Challenges:
201MHz RF in 3T field
0.1% meas. of emittance
LH2 safety issues

Single-μ beam
~200 MeV/c

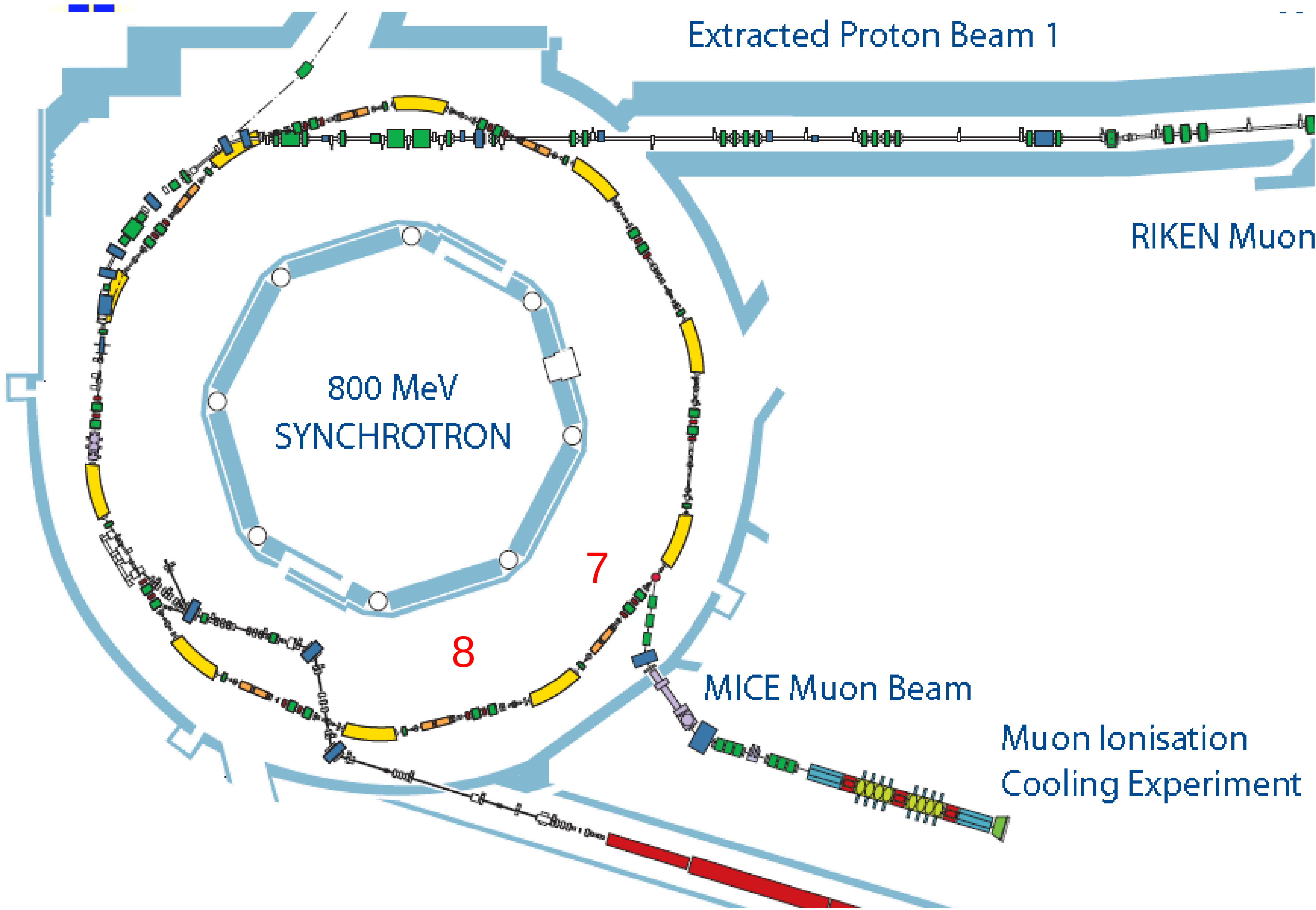
Some prototyping:


Scintillating-fiber tracker


MUCOOL Liquid-hydrogen absorber



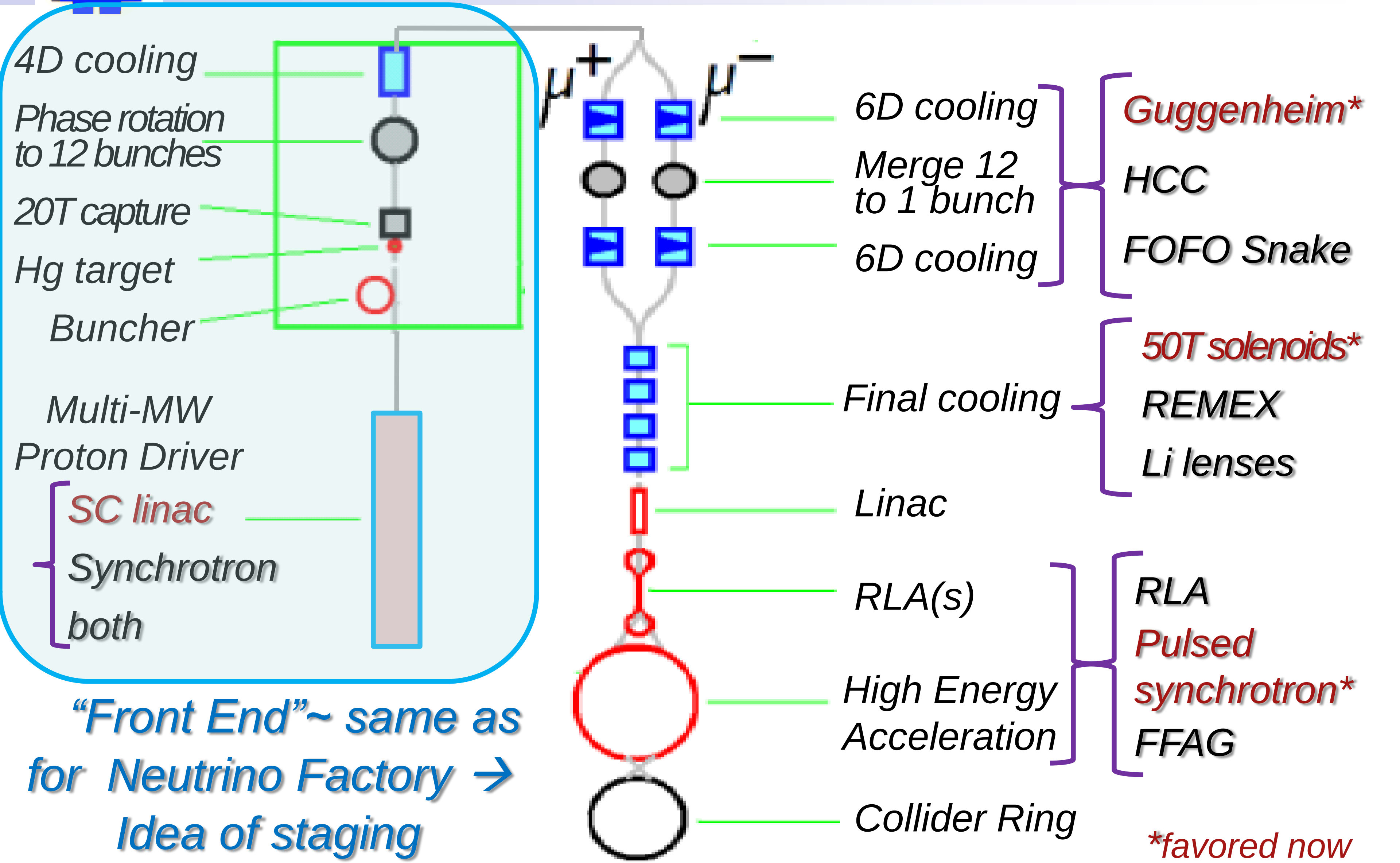

MUCOOL 201 MHz RF cavity with beryllium windows


Extracted Proton Beam 1
RIKEN Muon
800 MeV
SYNCHROTRON
7
8
MICE Muon Beam
Muon Ionisation
Cooling Experiment

MICE Experiment

- US contributes ~30% of the total cost

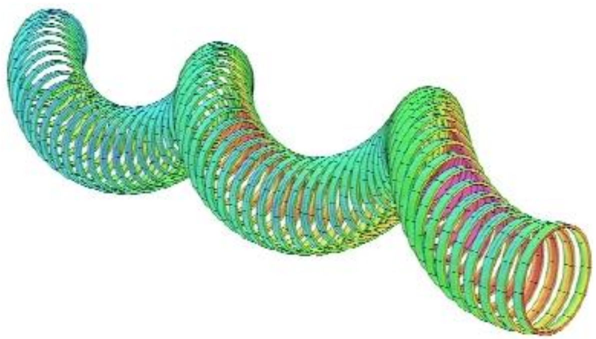
Muon Collider Scheme



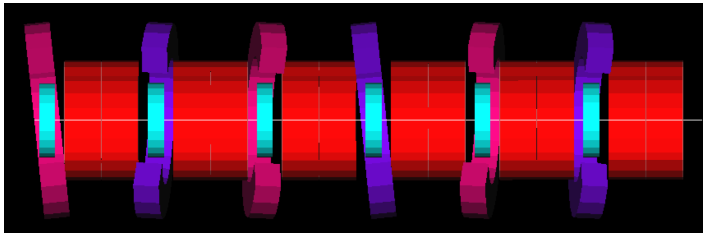
"Front End"~ same as for Neutrino Factory → Idea of staging

6D Cooling Channels

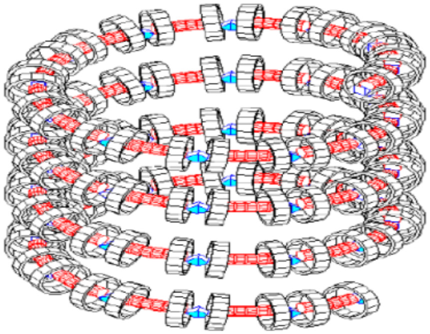
- Three main types (and many variants) of 6D cooling channel have been proposed, and **shown to cool in simulation**.



HCC
Derbenev/Johnson et .al



FOFO snake
Alexahin, et.al

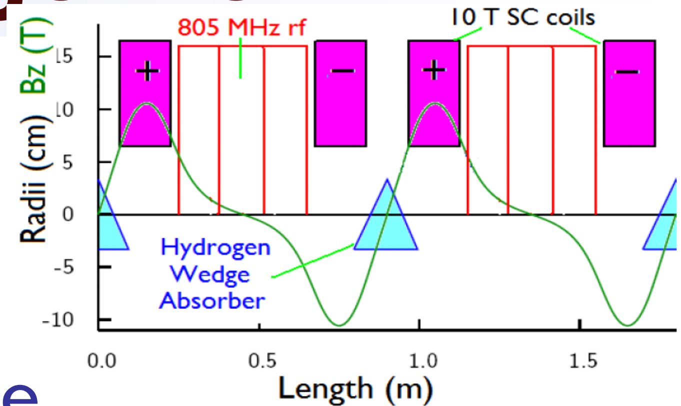


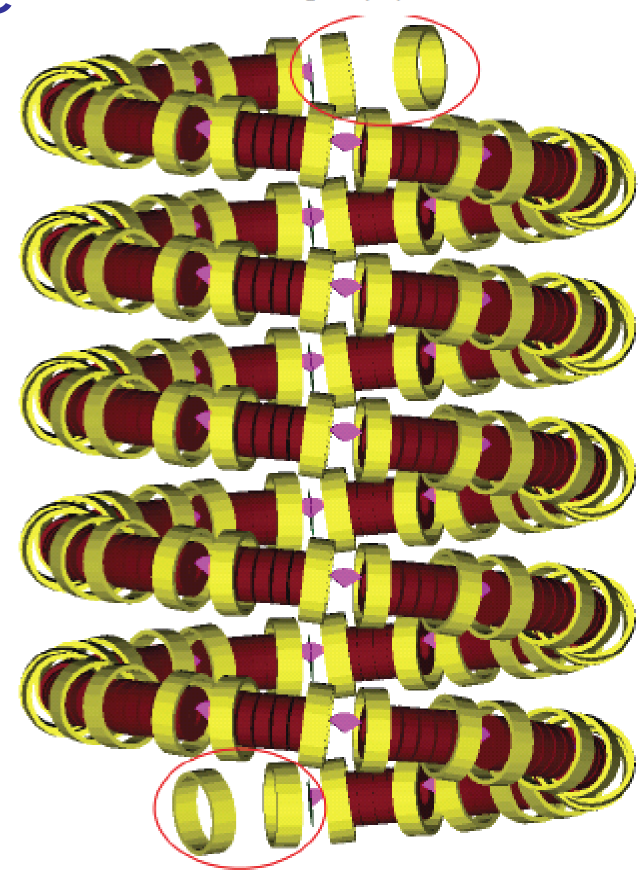
Guggenheim
Palmer, et. al

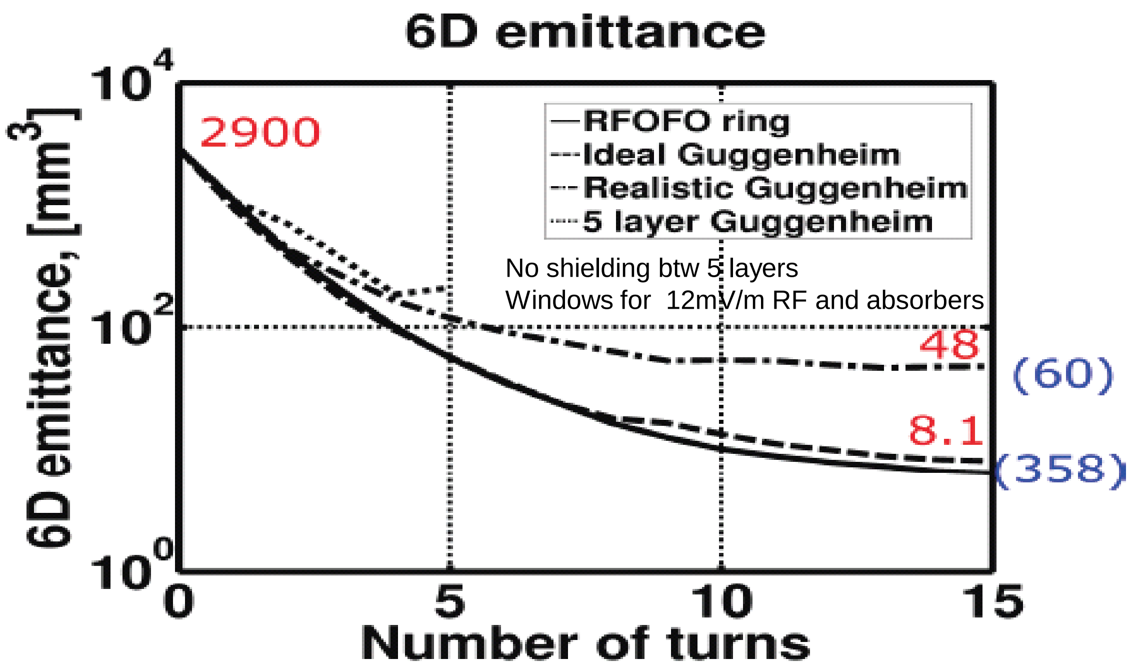
- They all require RF cavities operating in strong magnetic fields.
  - This is currently our biggest challenge

6D- Cooling: Guggenheim

- *Guggenheim* lattice
  - lattice arranged as helix
  - bending gives dispersion
  - higher-*p* = longer path in wedge absorbers → giving long. coolir
  - *Q: RF breakdown in 3-10 T field*







RF Breakdown Problem

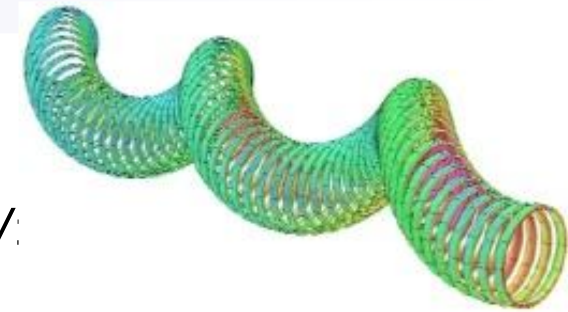
- Very serious:
  - lower gradient requires longer cooling channel as the total energy loss/restoration is given ~2-4 GeV
  - 200 MeV/c muons decay (63% over 2000 m)
- Possible ways to get around (to be studied)
  - better materials/processing
  - coating (e.g. Atomic Layer Deposition method)
  - "open iris" cavities (vs currently preferred pillbox with thin diaphragms)
  - explore dependence on B-field orientation
  - magnetic insulation : special configuration to have B || E

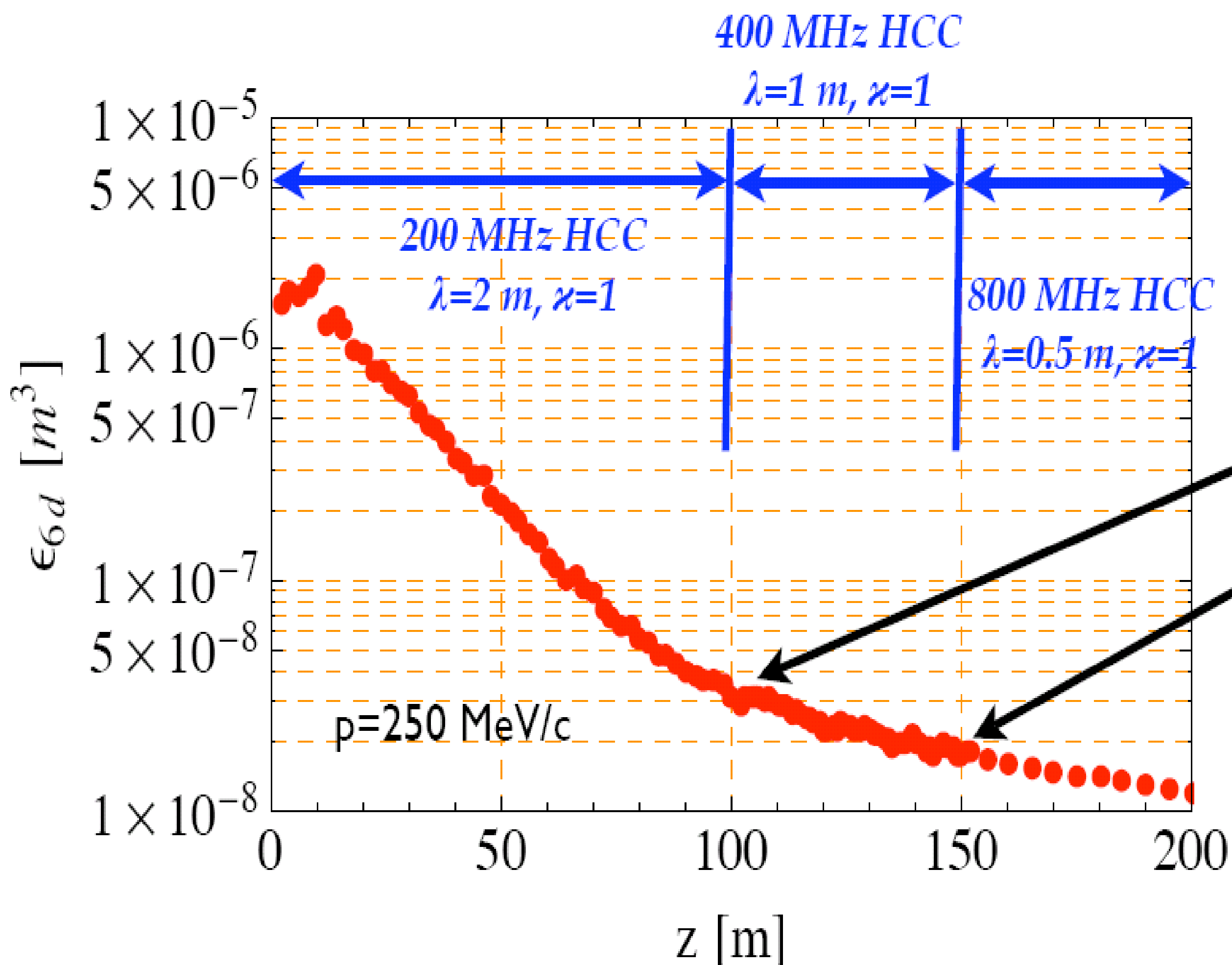
MTA=MuCool Test Area

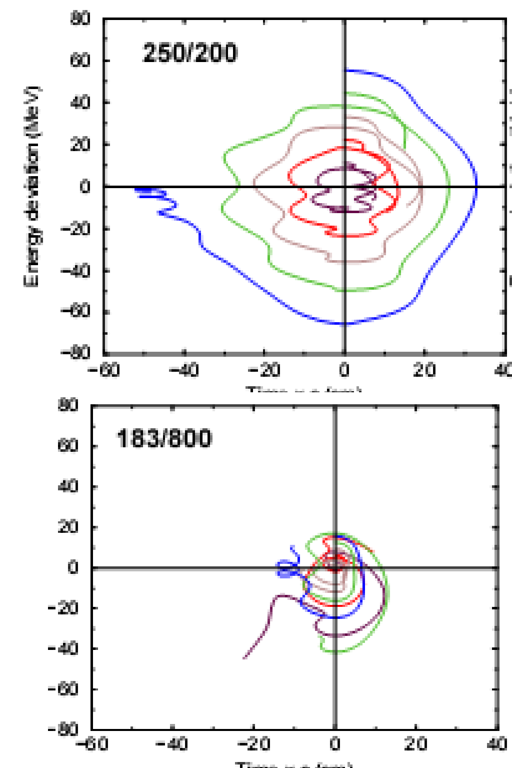
→ cryo
→RF p
→ Liqu
→ 5 T S
(805
→ 400M

Helical Cooling Channel

- Pressurized H2 inside RF:
  - absorber needed for cooling
  - Helps to increase RF gradient – need ~15MV/

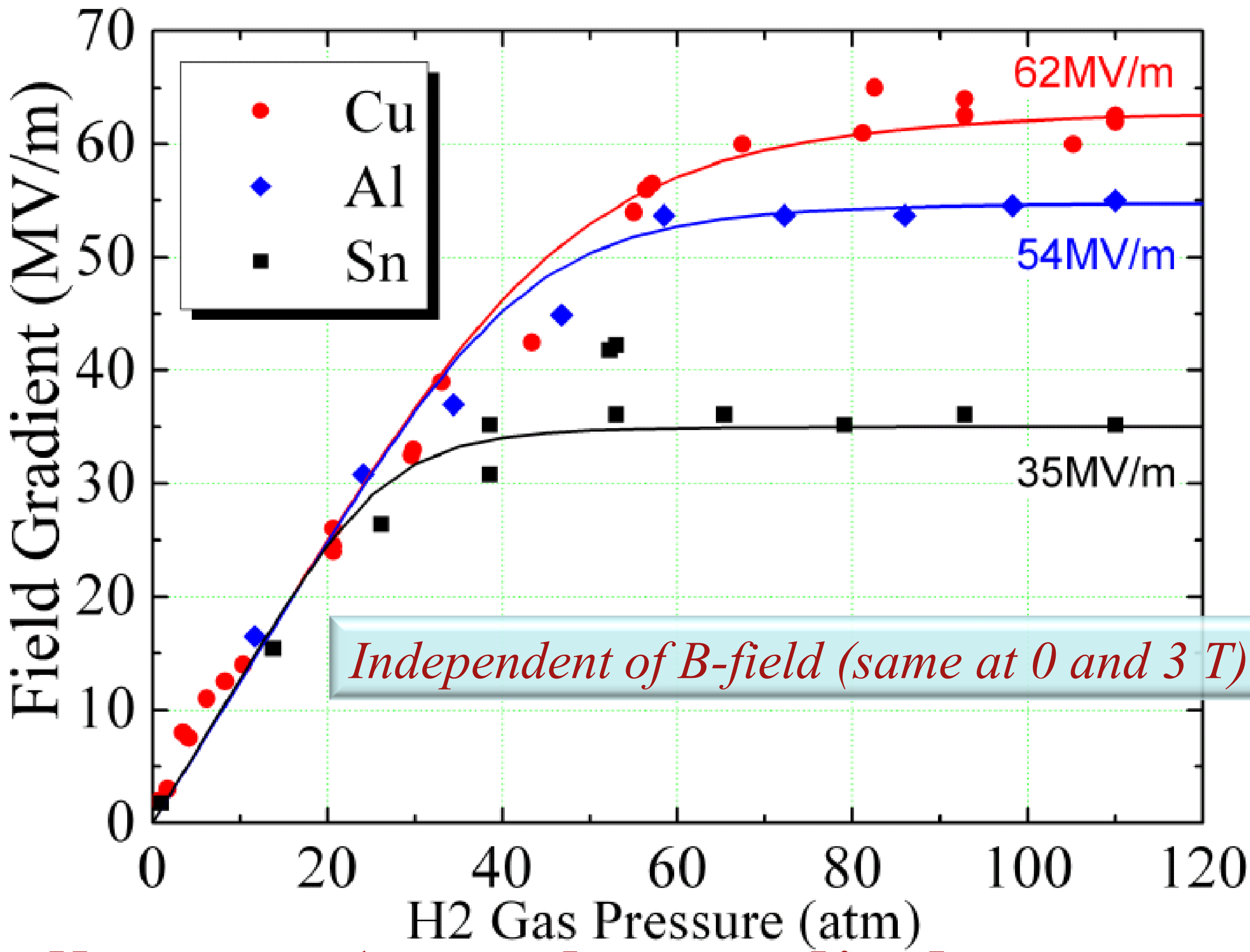






Perturbation of longitudinal motion by betatron oscillations decreases the channel acceptance

High Pressure RF Tests in MTA

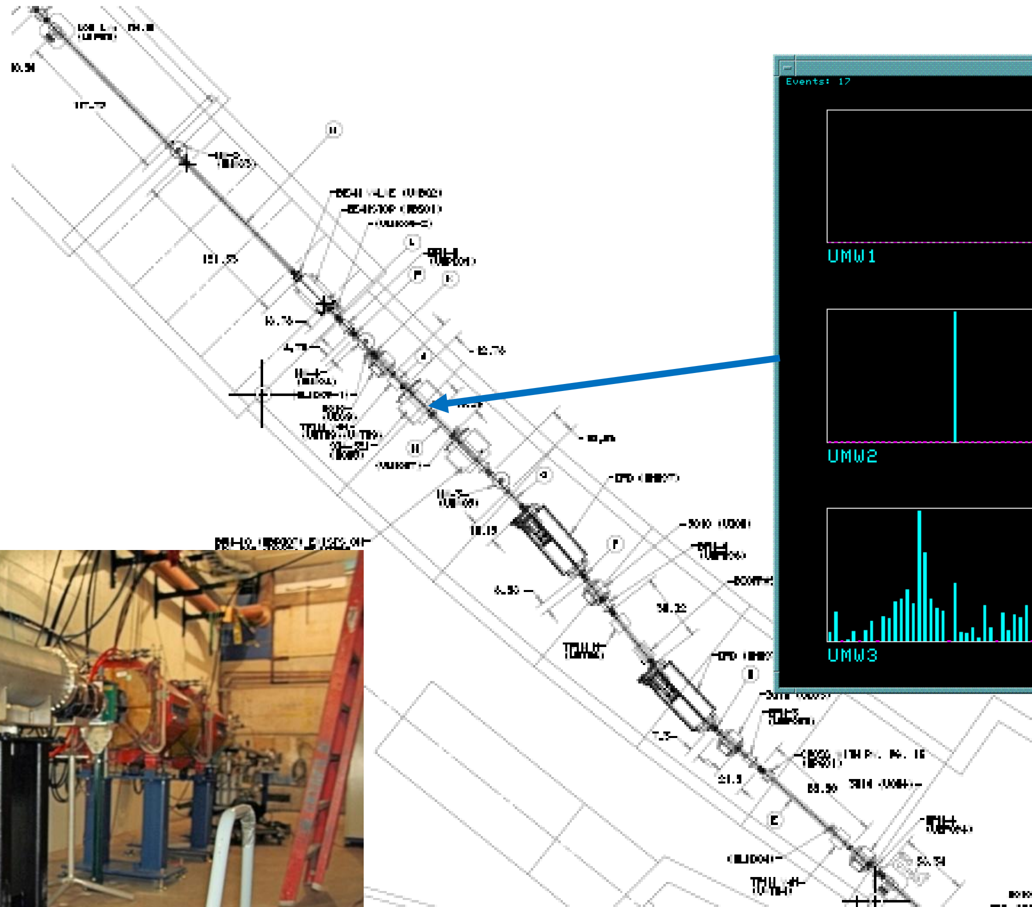


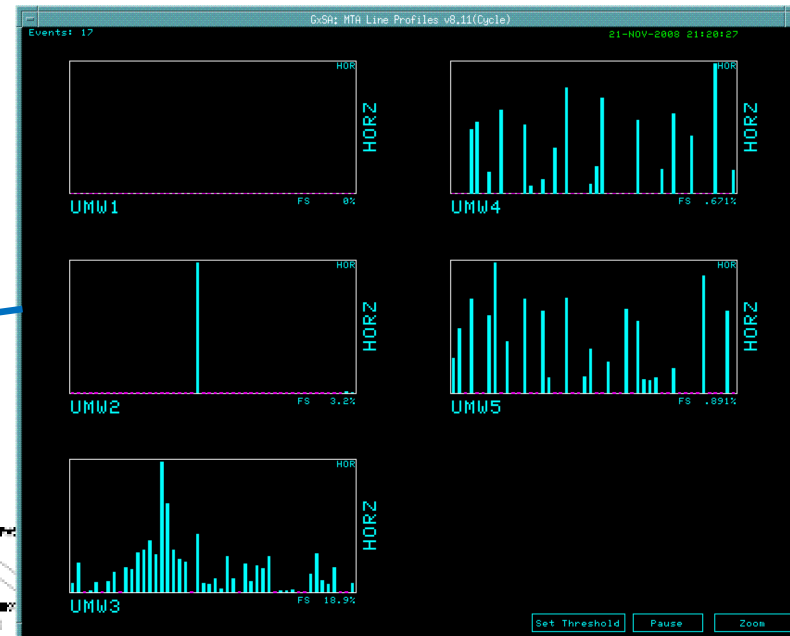
Independent of B-field (same at 0 and 3 T)

- **Challenges (must be studied)**
  - how to fit "usual" RF inside helical magnet with fixed geometry
  - will RF cavity work if the gas is ionized by muons ?

Proton beam to MTA Hall

Beam to first beam stop, visible on multiwire 3m upstream

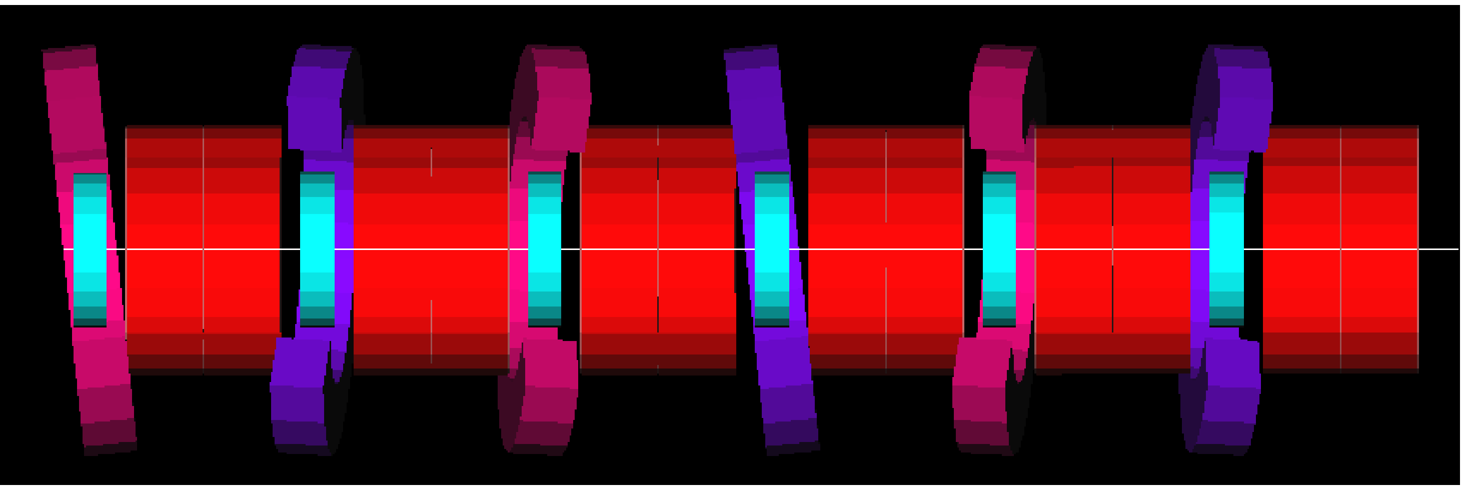


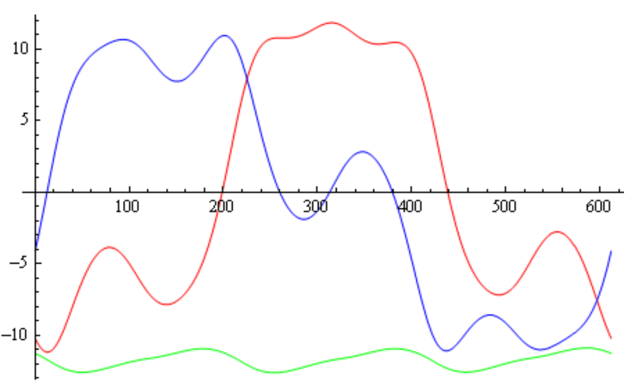


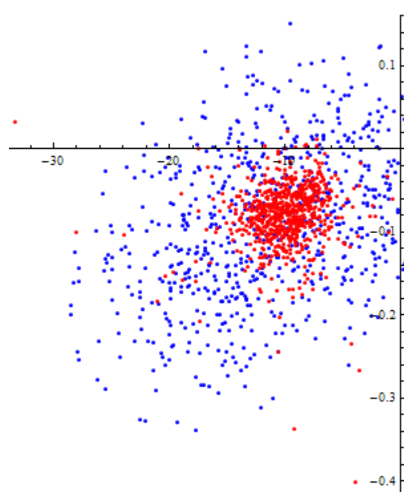
“FOFO-Snake” 6D Cooling

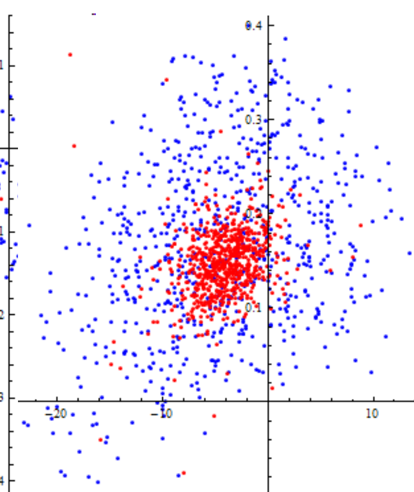
- Very promising and less technologically challenging scheme

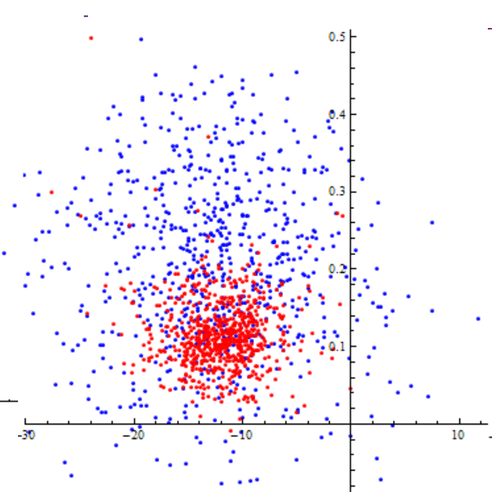
The only scheme which cools both μ+ and μ-!





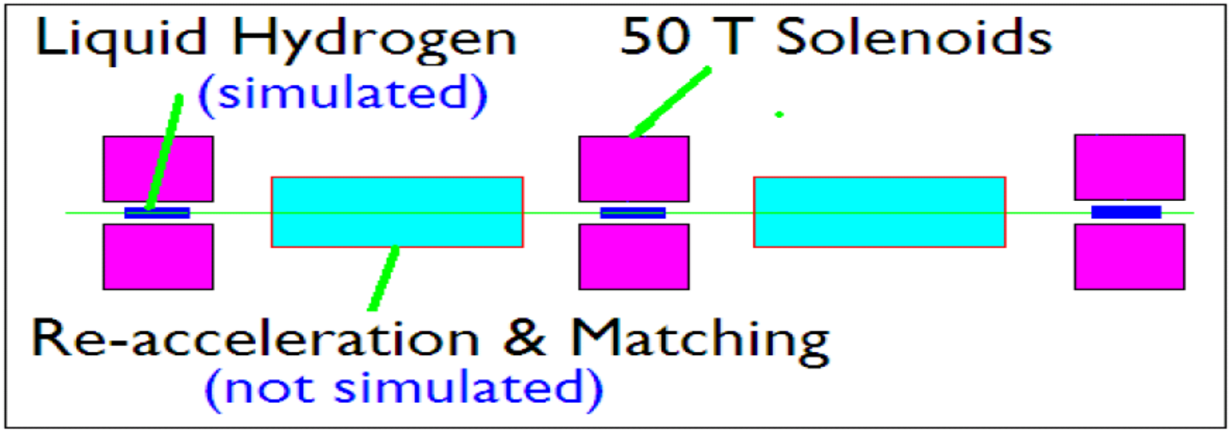


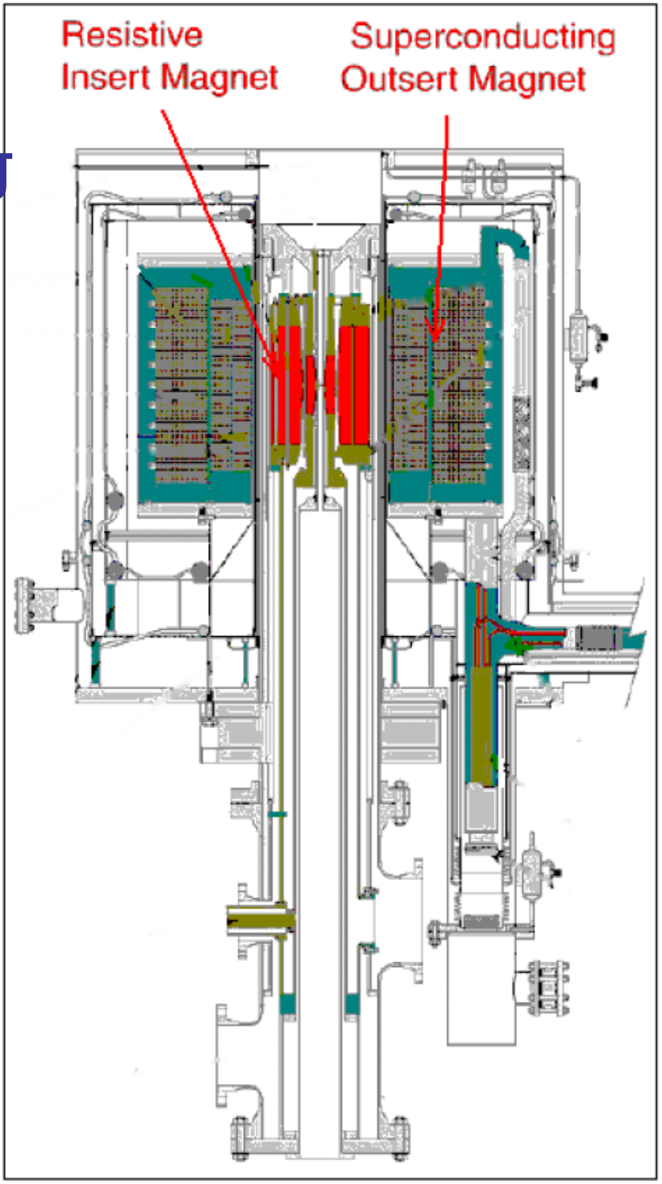




"Final-" Transverse Cooling

- **High Field Solenoids:**
  - low momenta and strong focusing allow low transverse emmittance
  - longitudinal emittance rises

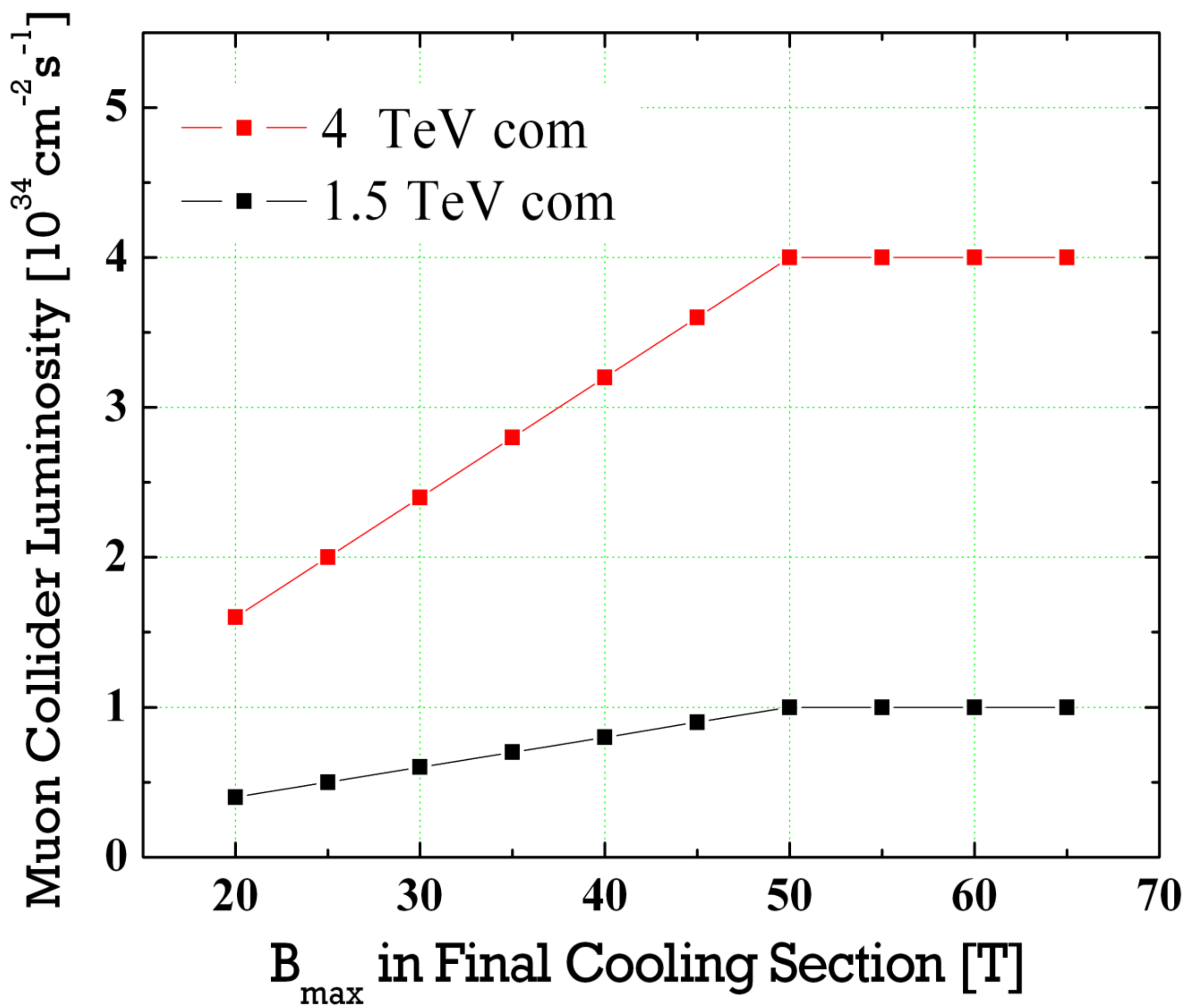




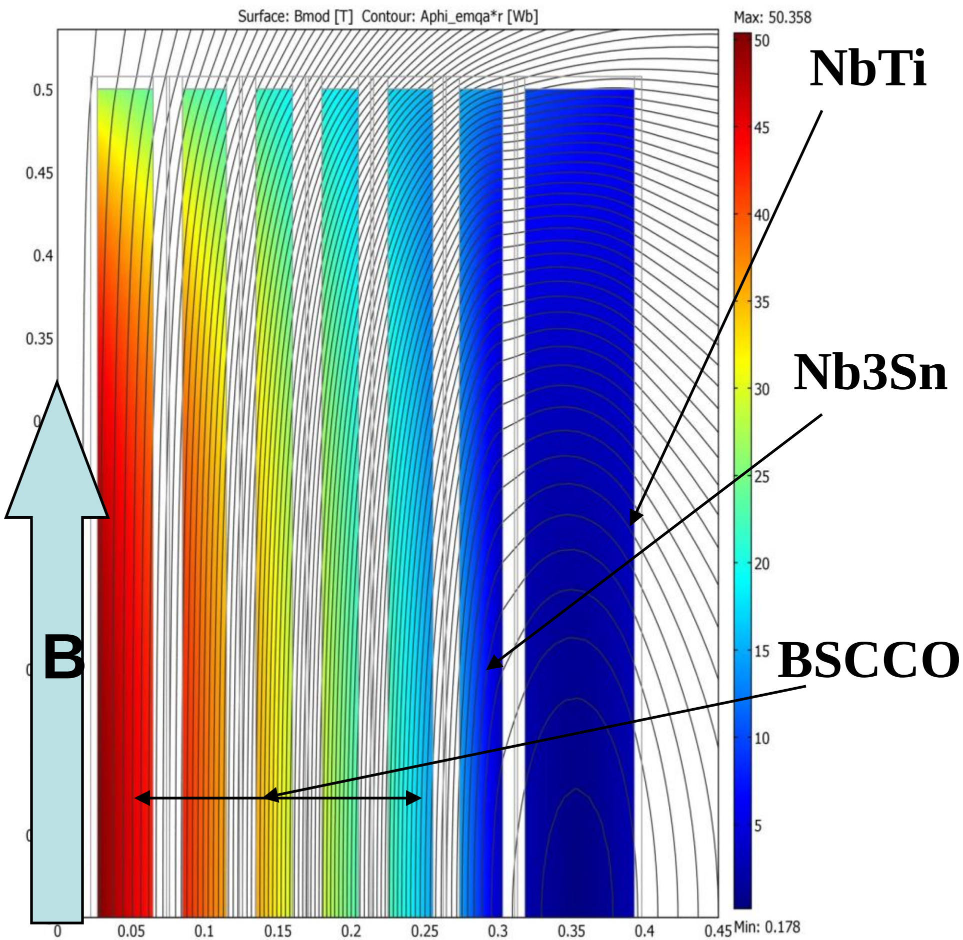
NHMFL 45 T Hybrid Magnet

- **Issues :**
  - ✓ need up to 50T fields solenoids
  - ✓ Transverse matching
  - ✓ acceleration of very long bunches

High Field Solenoids



50 T Solenoid Concept



Coil radius, m

Basic Parameters

- Inner bore diameter 50 mm
- Length 1 meter
- Fields 30 T or higher ➔
  - HTS materials

Key design issues:

- superconductor Jc
- effect of field direction on Ic in case of HTS tapes
- stress management
- quench protection
- cost

Conceptual design:

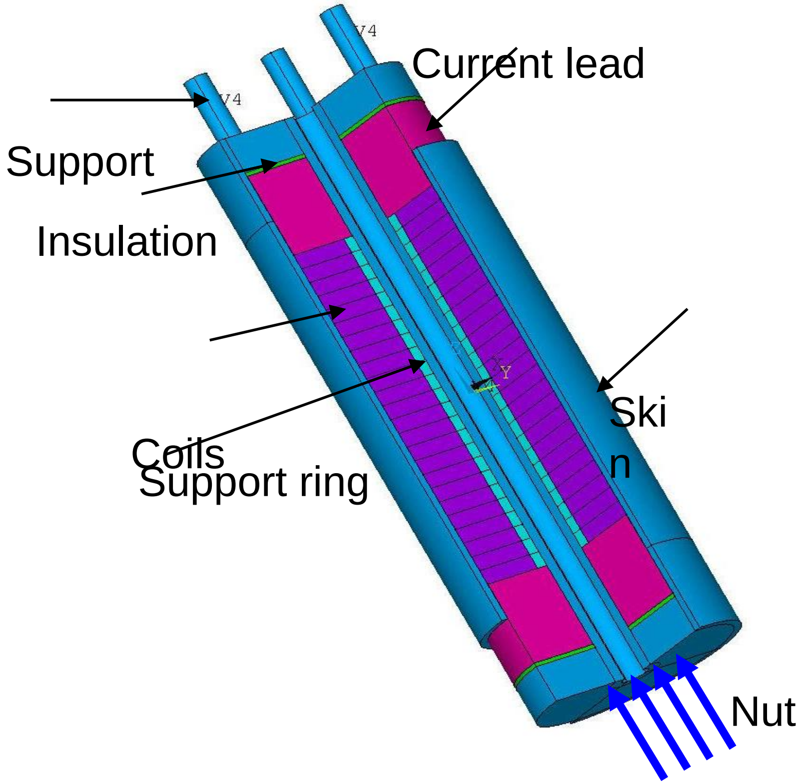
- hybrid coil design
- coil sections

Work in progress:

- Conductor
- Quench protection

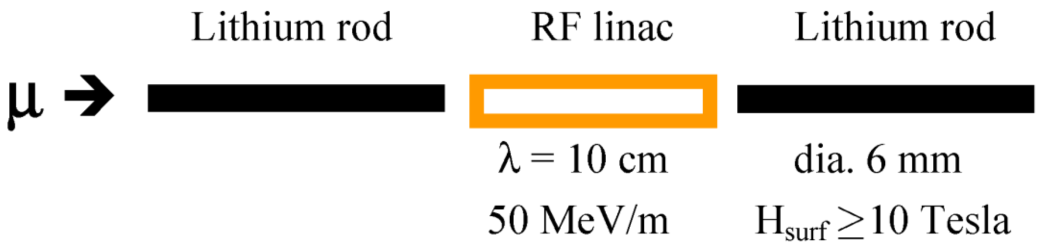
HTS Magnet R&D

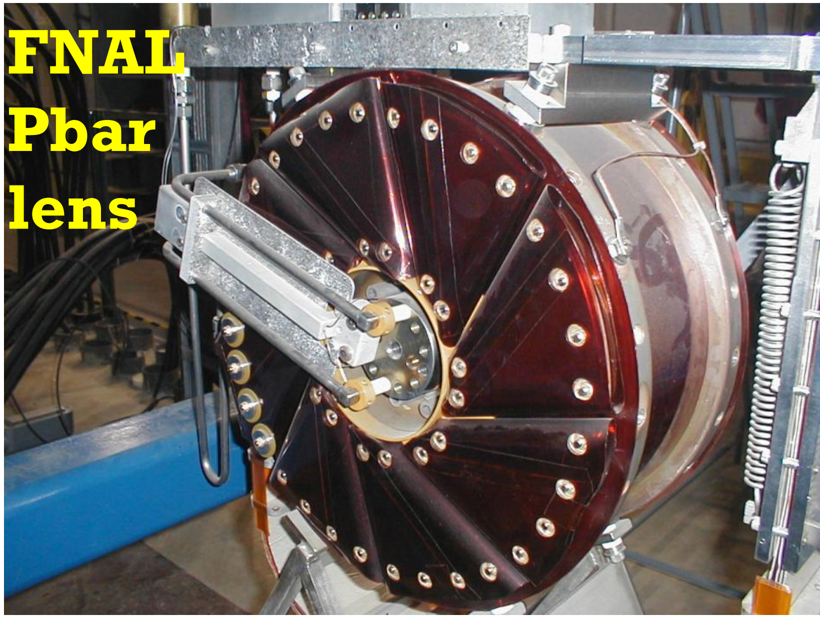
- Single and double layer HTS coils designed and tested:
  98%-22% of SSL!
- Modular HTS test facility designed and being procured
  - Test many coils inside 16T solenoid
- BSCO-2212 cable and wire work will be done within National Collaboration



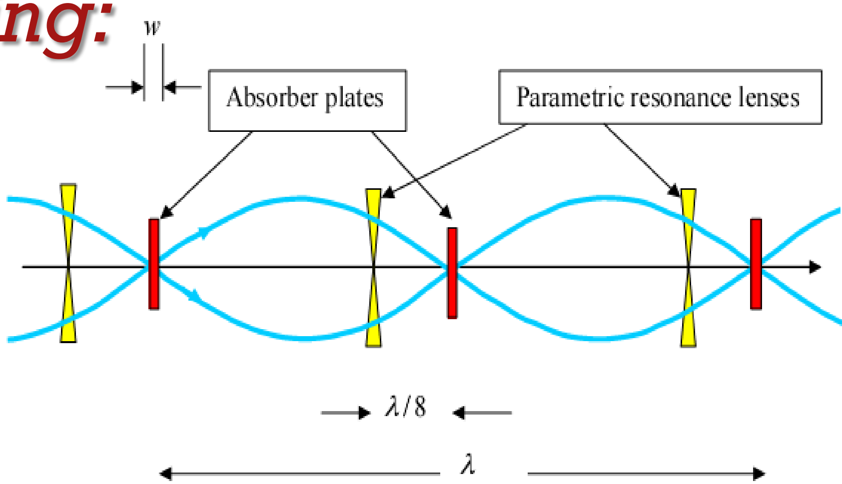
"Final-" Cooling (alteratives)

- ***Li lenses=focus + absorb:***
  - strong (*eg* 1MA, 1cm, 40T)
  - *limited rep.rate 0.5Hz → 5-10Hz → Liquid ?*



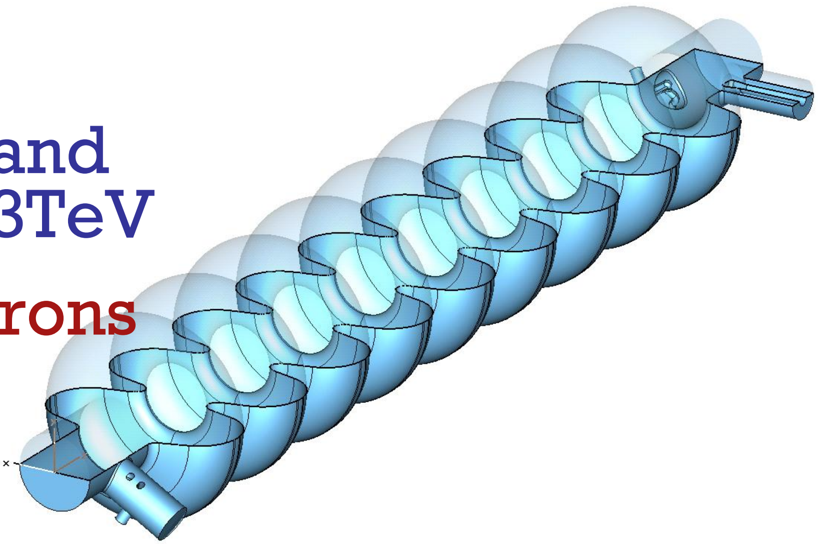


- ***Parametric Ionization Cooling:***
  - ½ integer resonance optics
  - very low beta's
  - *Aberrations! (dp/p, geometric)*
  - *Space-charge effects*

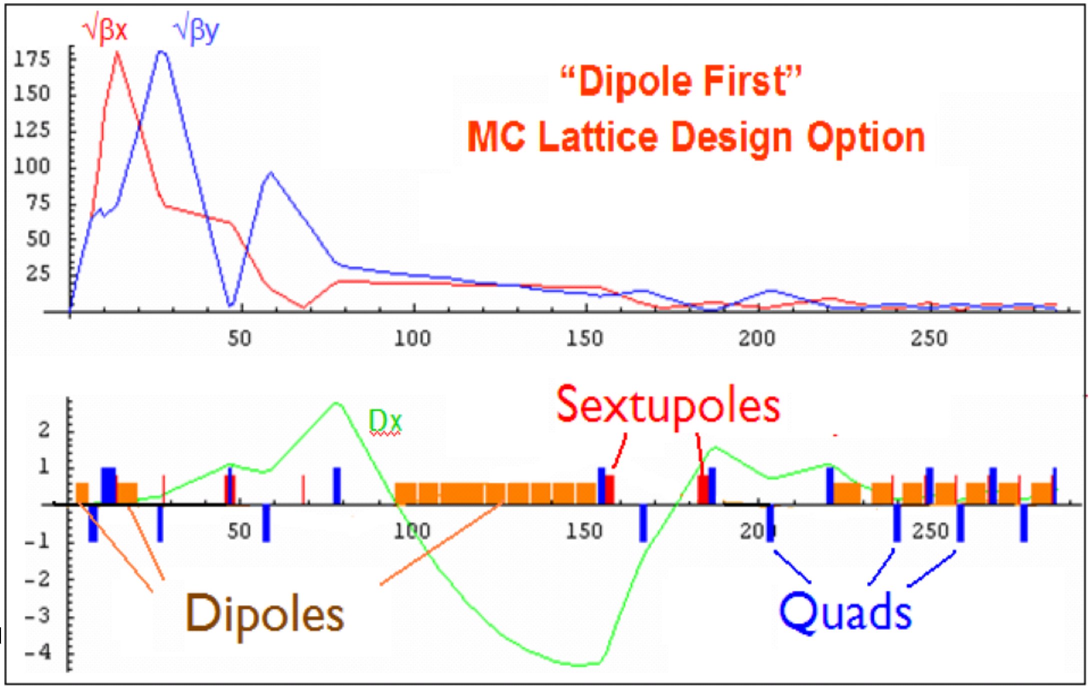


Acceleration and Collider

- Acceleration
  - rapid acceleration in linacs and RLAs, <90MW wall plug for 3TeV
  - lower cost – pulsed synchrotrons *prototyping needed*
  - FFAGs can also play a role

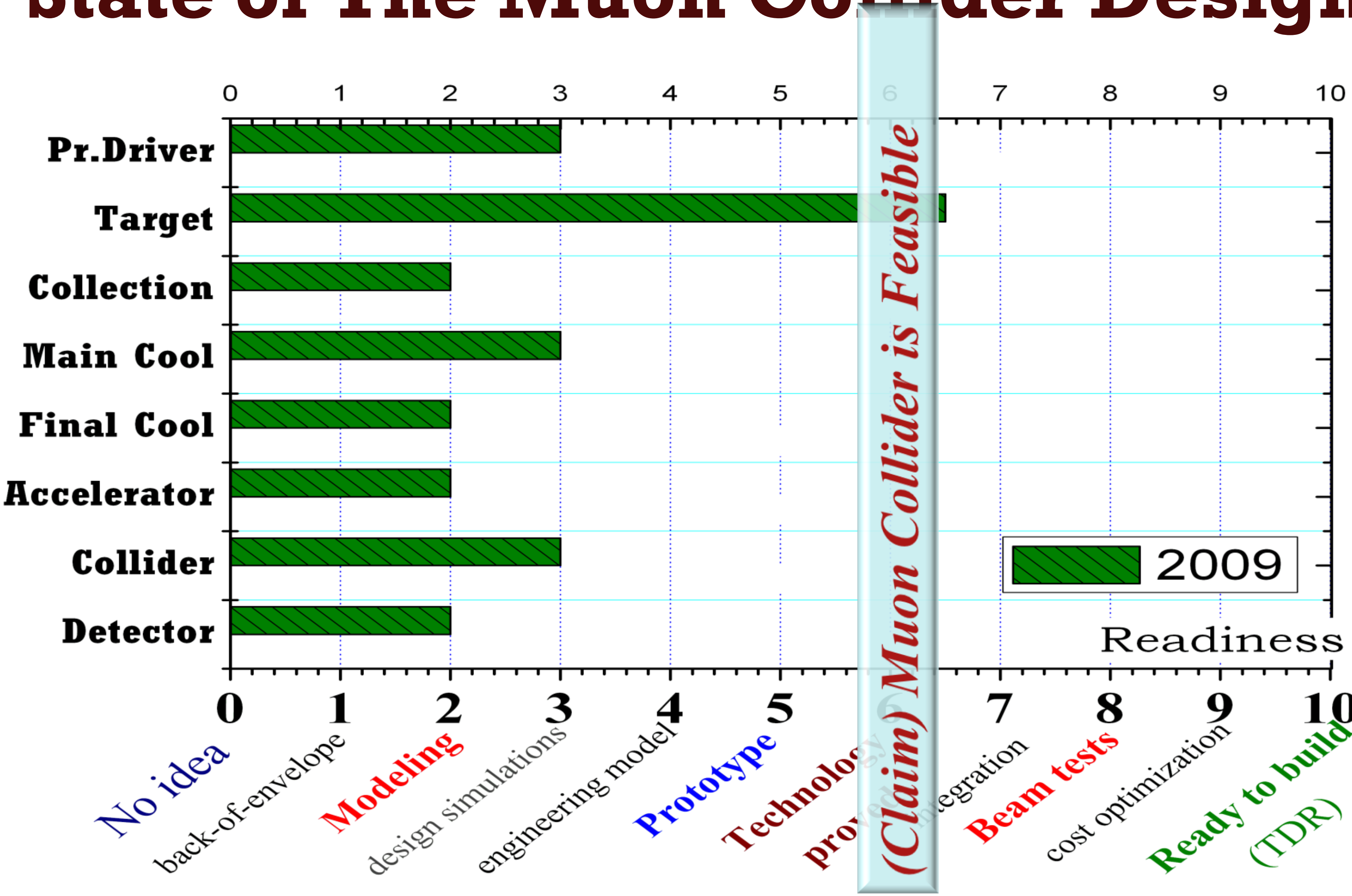


- Collider Ring
  - 1.5 TeV designed
  - *to be studied: Detector backround with early dipole scheme*

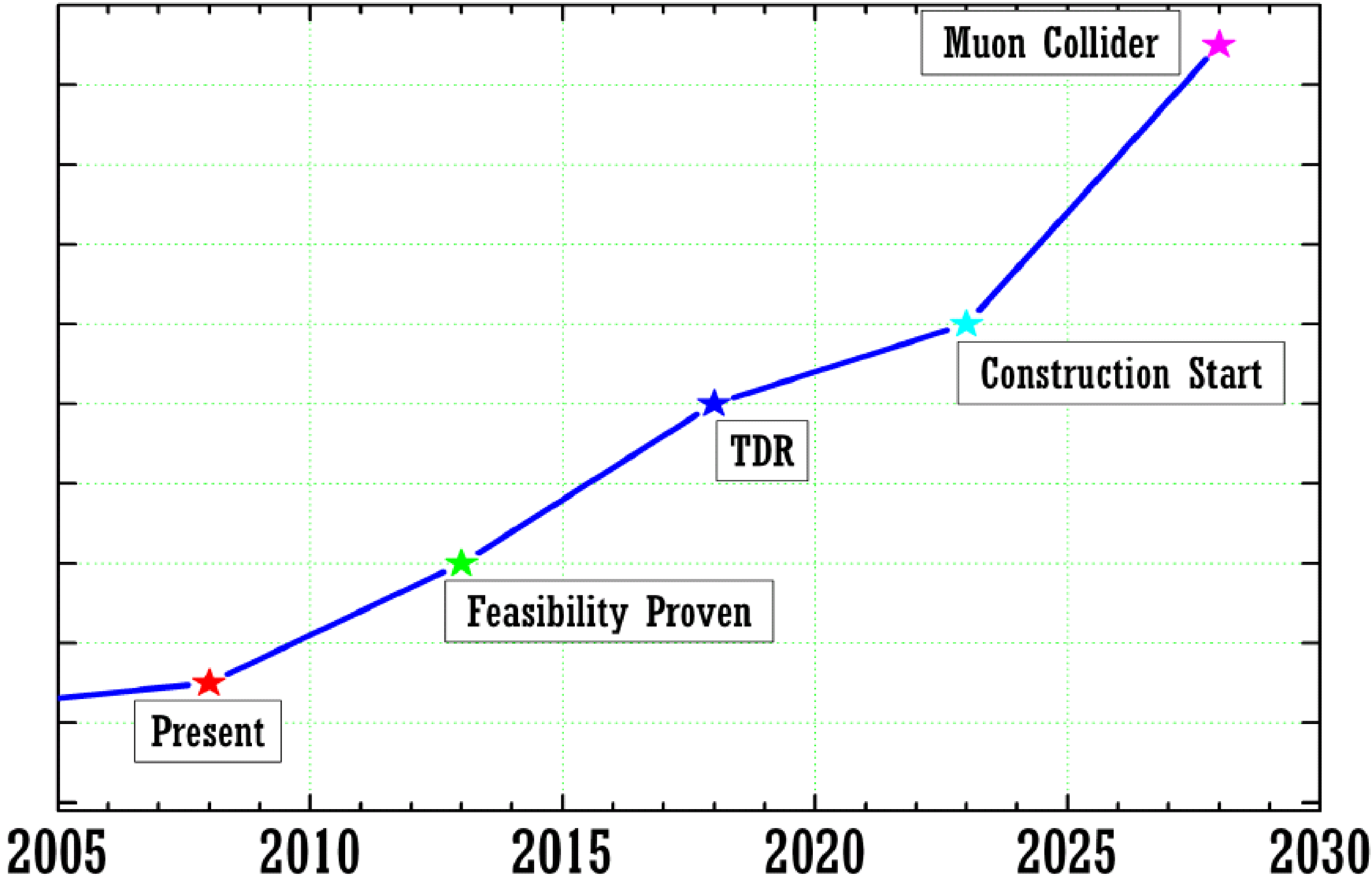


Where Are We Now?

State of The Muon Collider Design



Where Do We Want to Be and When?



Why Are We So Much Behind?

- **Insufficient Funding:**
  - about 4-5M$/year in 2000-2006 total M&S and SWF
  - about 8M$/year now (since MCTF created in ‘06)
  - still factor of 3 less than needed
- **Problems are numerous and complex:**
  - for most of them we see solutions
  - for most of them there are several (3) – all very attractive
  - down-selection needs INPUT (= high priority R&D)
- **Not enough people**
  - about 15 FTEs before 2006, some 30 now
  - sometimes – not enough coordination

What Is Needed?

- First of all – we need a good **PLAN**
  - What - Who -When - How Much
- Then we need to get **support**
  - kind of MCSP=Muon Collider Stimulus Package
- **Plan has been made!**

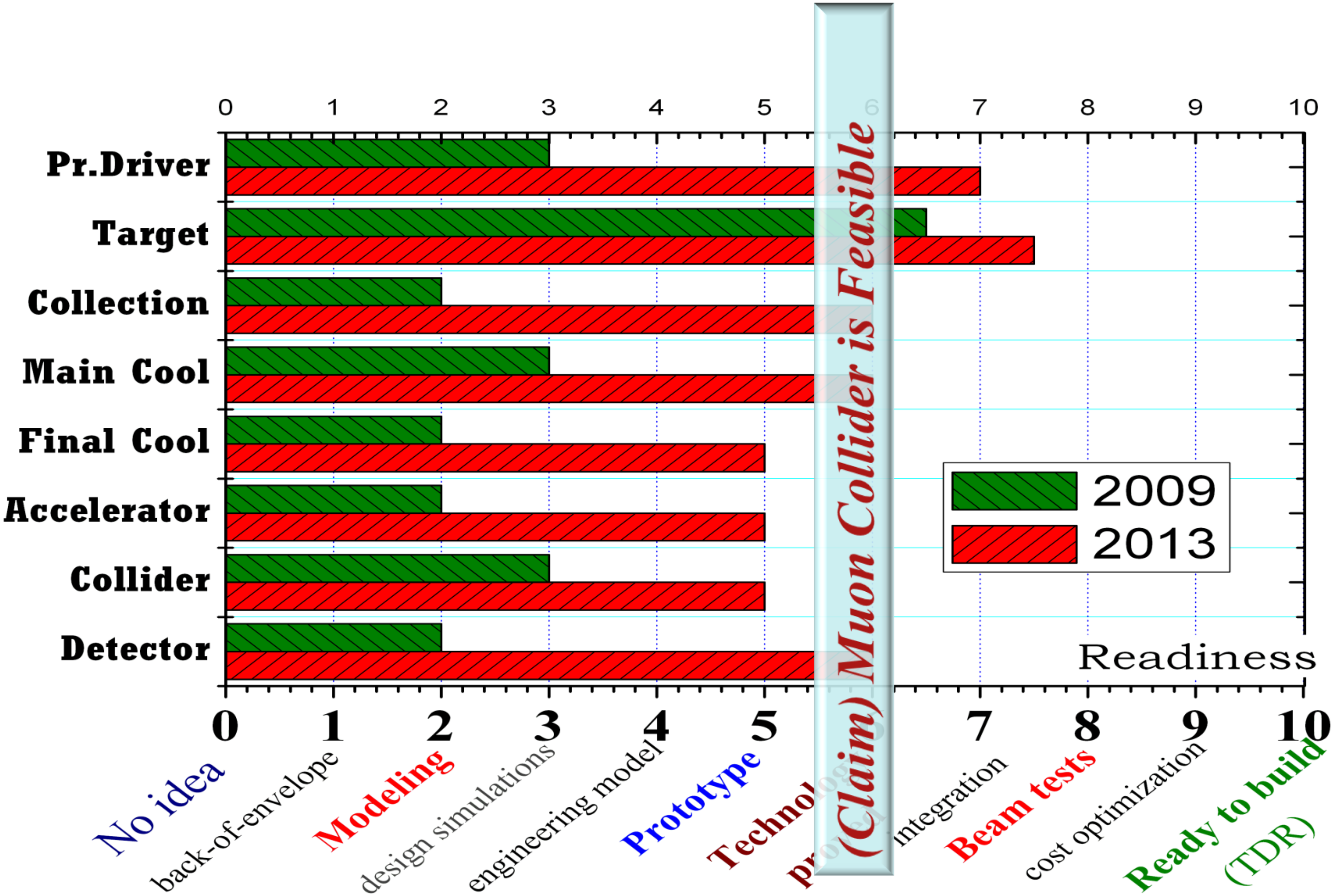
US Muon Accelerator R&D Program
5 yr plan (2009-2013)

- Program Management
  - 1. Design
    - 1.1 Physics & Detector
    - 1.2 Design& Simulations
    - 1.3 Cost Estimate
    - 1.4 NF IDS/RDR
  - 2. Components and tests
    - 2.1 MICE
    - 2.2 Cooling Ch. RF
    - 2.3 Magnets
    - 2.4 6D Cooling comp &test
    - 2.5 Other R&D

The 5 Year Plan

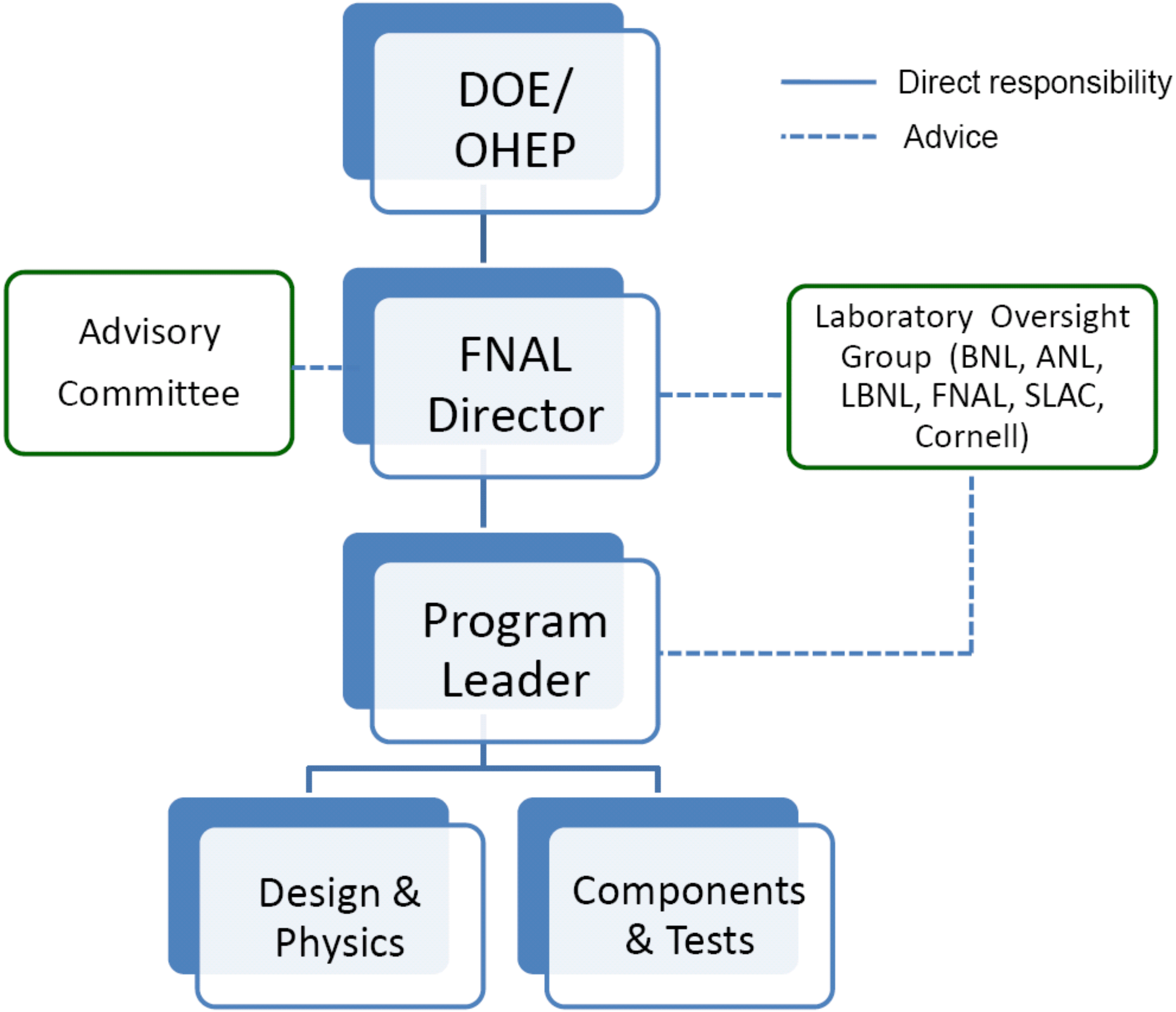
- **Will address key R&D issues, including**
  - Maximum RF gradients in magnetic field
  - High pressure RF tests with ionizing beam
  - 6D cooling section prototype
  - Full start-to-end simulations
  - Proton bunching ring design
  - Magnet designs for acceleration, collider and HTS
- **Deliverables by ~2013:**
  - Muon Collider Feasibility Report and ν-Factory RDR
  - Results of hardware R&D to make technology choice
  - Cost estimate
- **Funding increase needed to ~20M$/yr (about 3x present level); total cost 90M$**

5 yrs of Muon Collider R&D



We Have to Take the Lead!

If not Fermilab, then who?



5-Year Plan of Muon Accelerator R&D

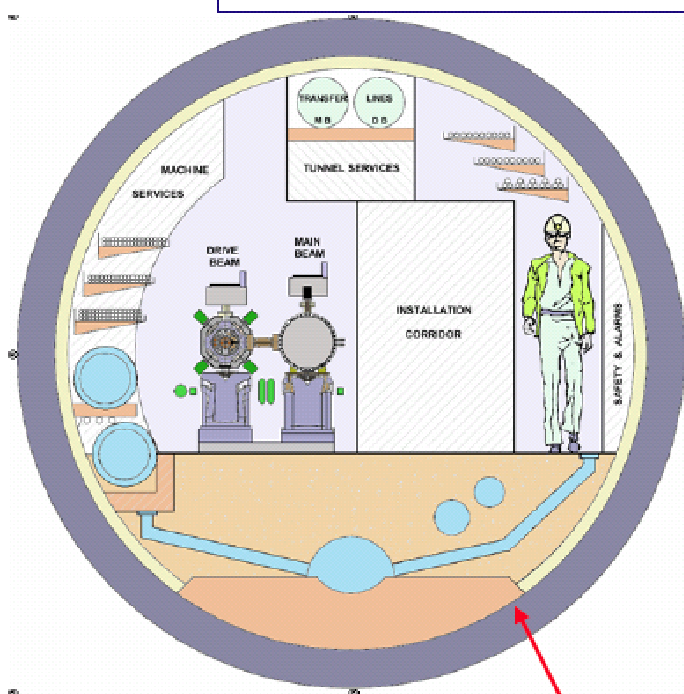
- v1.0 presented to MUTAC in Aug'08
- 1 hr briefing of D.Kovar Nov'08
- Presented at the Dec'08 DoE review of Accelerator Science
  - Outlined by the "central team"
  - Elaborated coherently in presentations of 4 labs
    - FNAL, LBNL, BNL and ANL
- Formally submitted to DoE in Dec'08
  - Accompanied by letter from 3 Assoc.Lab.Dir's
- Current status: seeking review by DOE OHEP

CLIC Concept

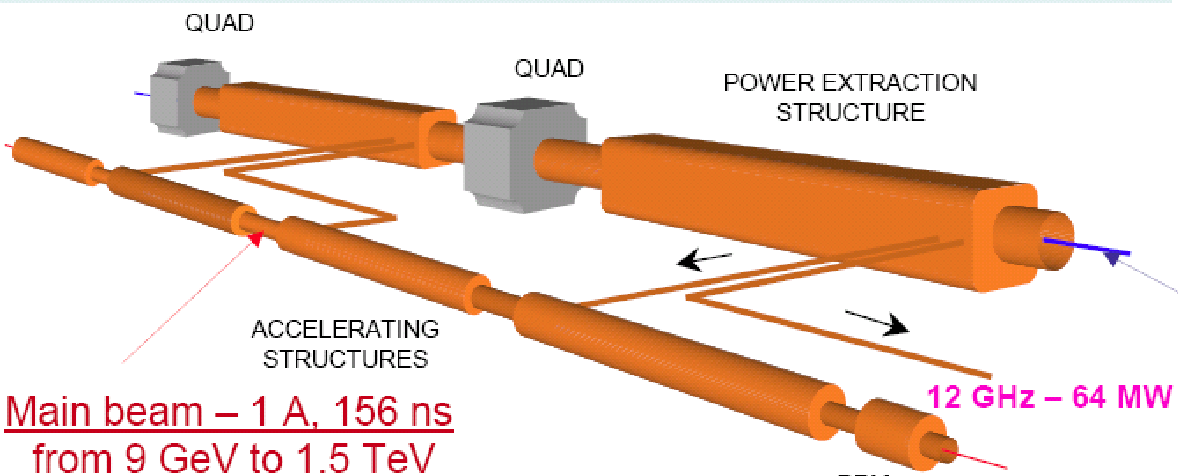
- **High acceleration gradient: > 100 MV/m**
- "Compact" collider – total length < 50 km at 3 TeV
- Normal conducting acceleration structures at high frequency

- **Novel Two-Beam Acceleration Scheme**
  - Cost effective, reliable, efficient
  - Simple tunnel, no active elements
  - Modular, easy energy upgrade in stages

CLIC TUNNEL CROSS-SECTION



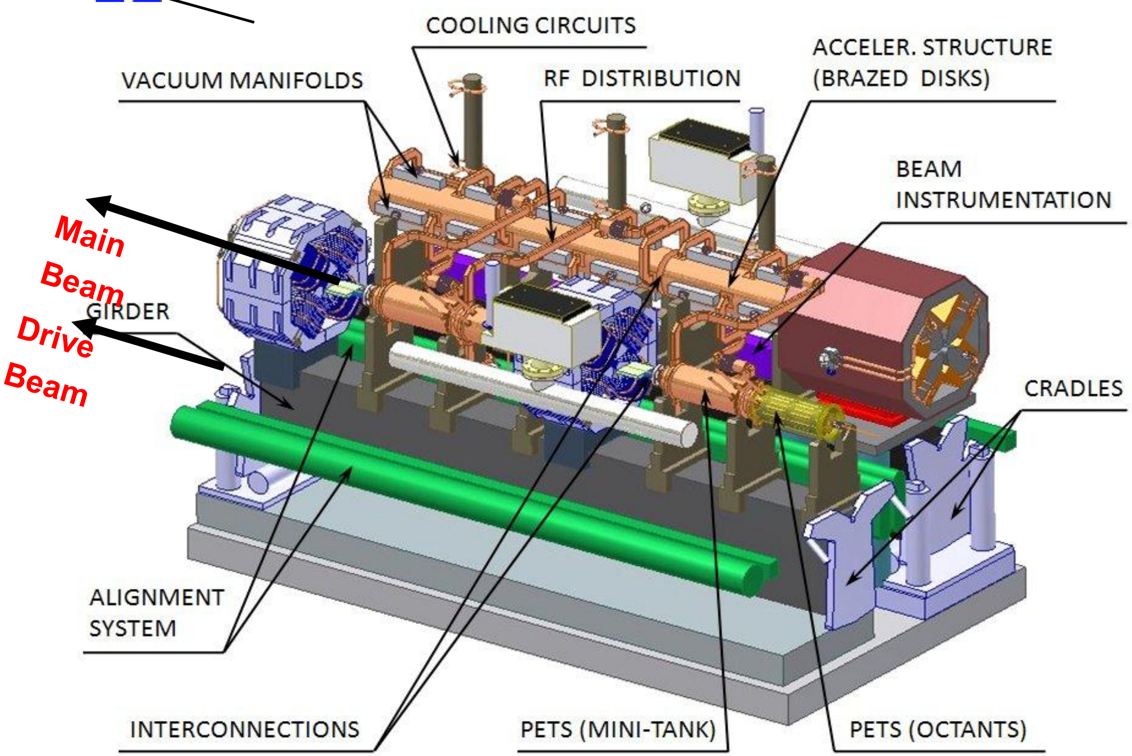
4.5 m diameter

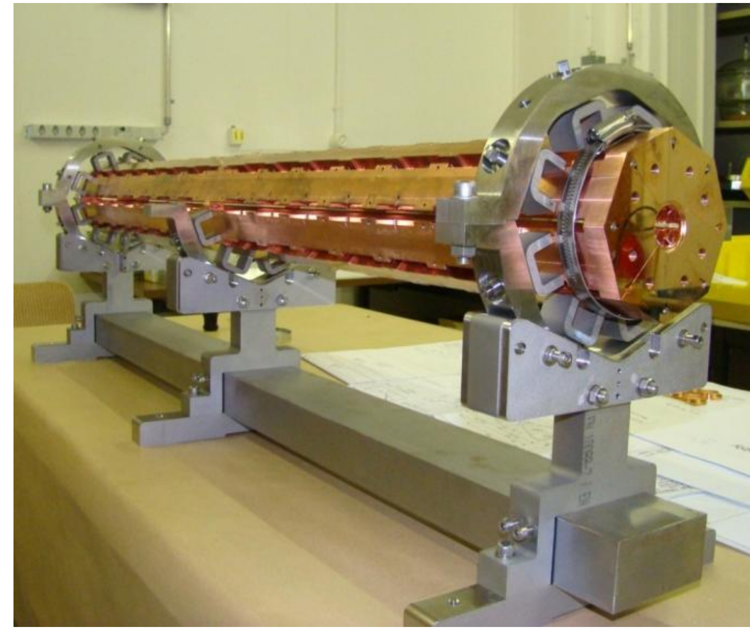


Drive beam - 95 A, 240 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 156 ns
from 9 GeV to 1.5 TeV
100 MV/m

CLIC Accelerating Module



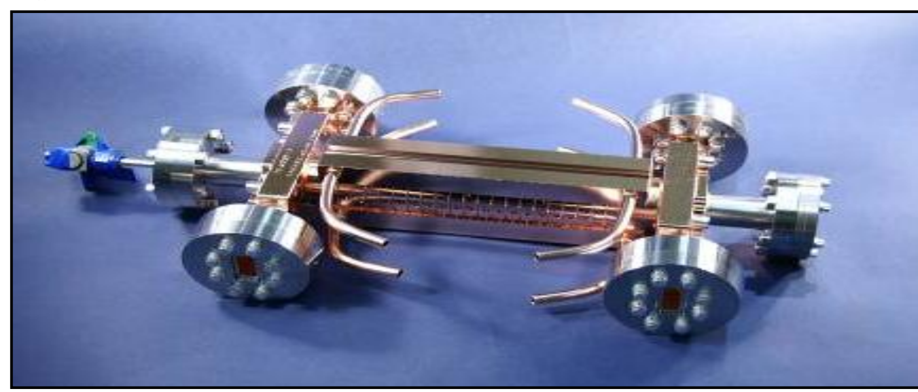


20760 modules (2 meters long)

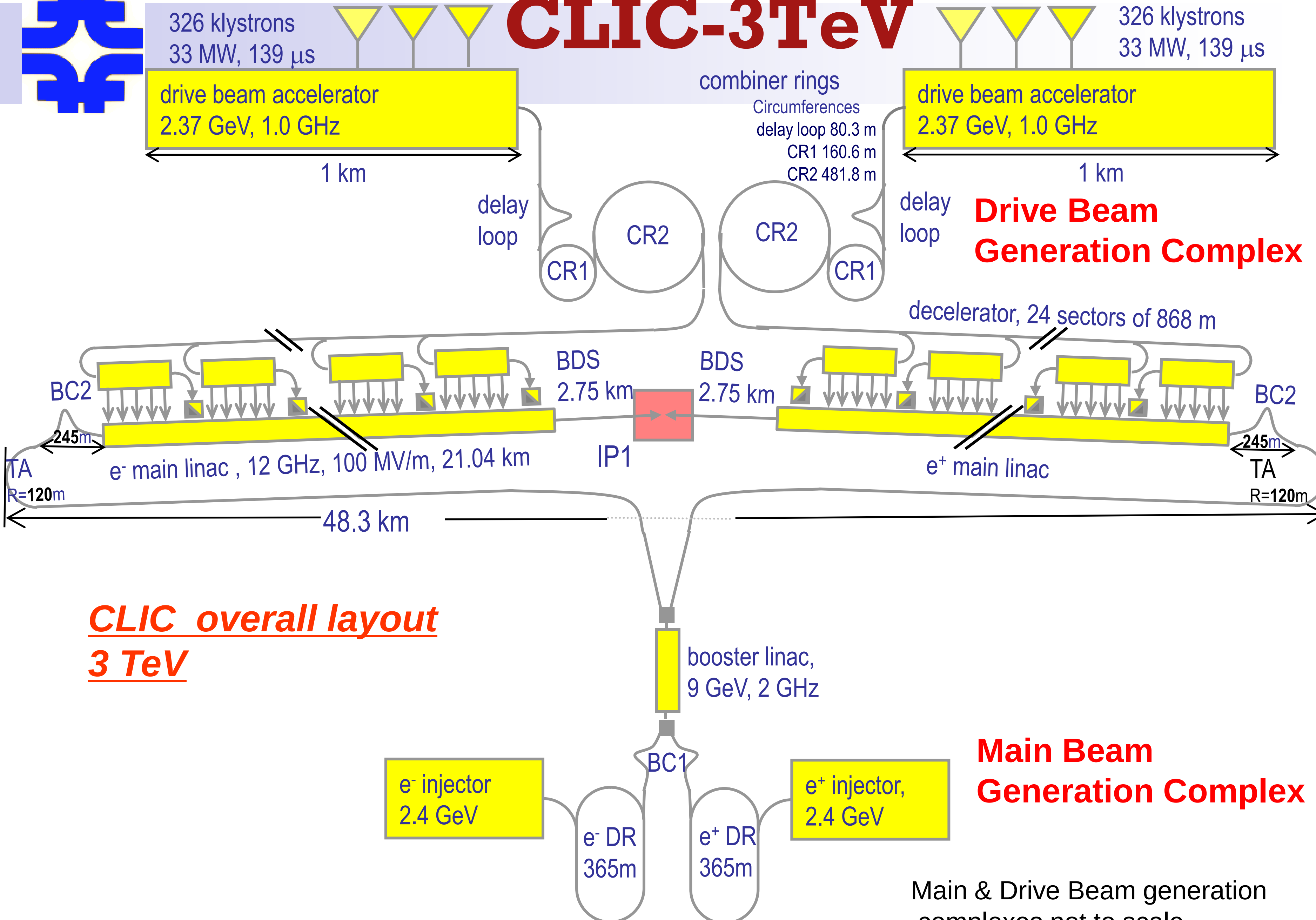
71460 power production structures PETS (drive beam)

143010 accelerating structures

(main beam)



CLIC-3TeV

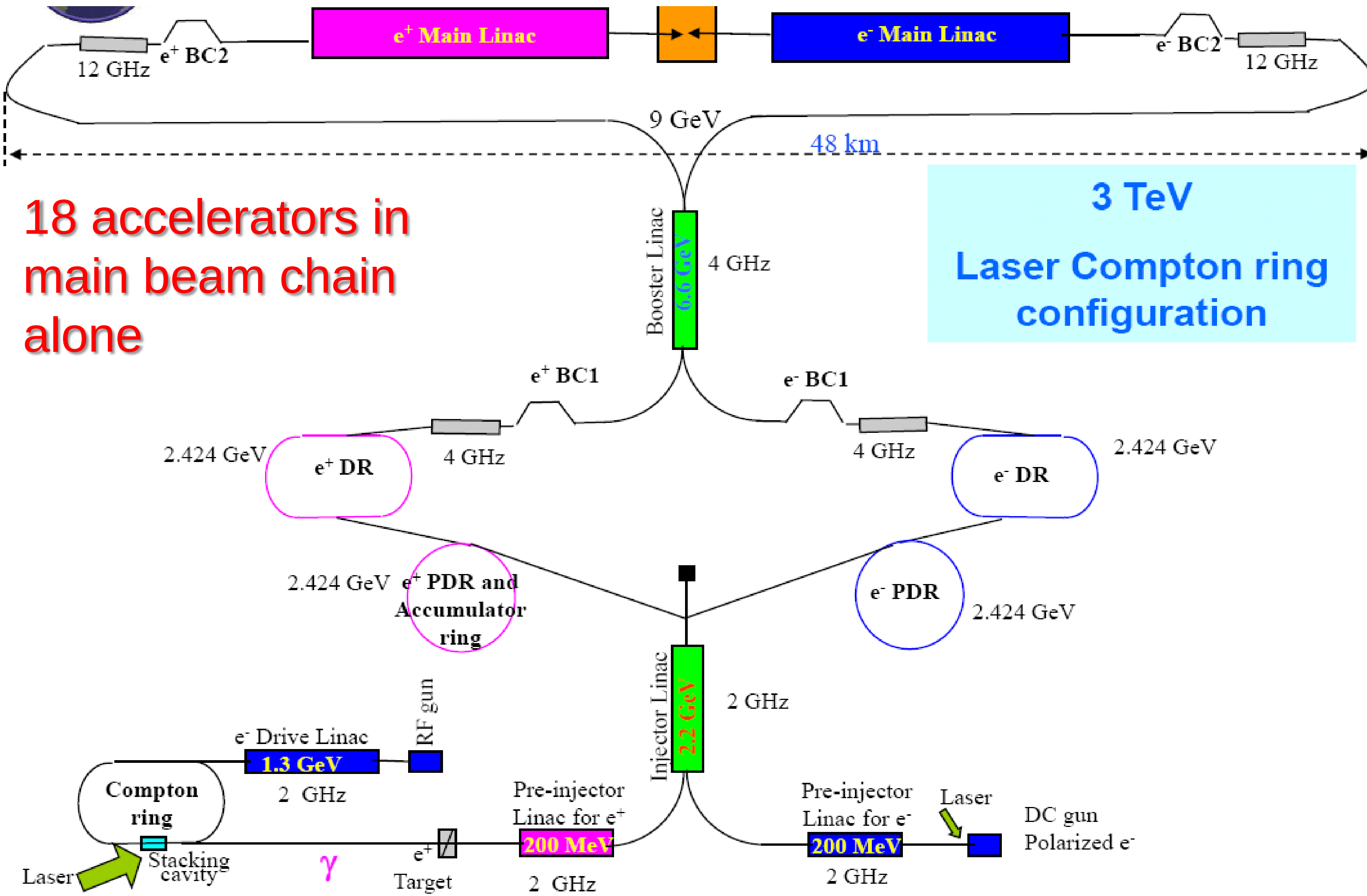


CLIC overall layout 3 TeV

Main & Drive Beam generation complexes not to scale

CLIC = MANY Accelerators

18 accelerators in main beam chain alone

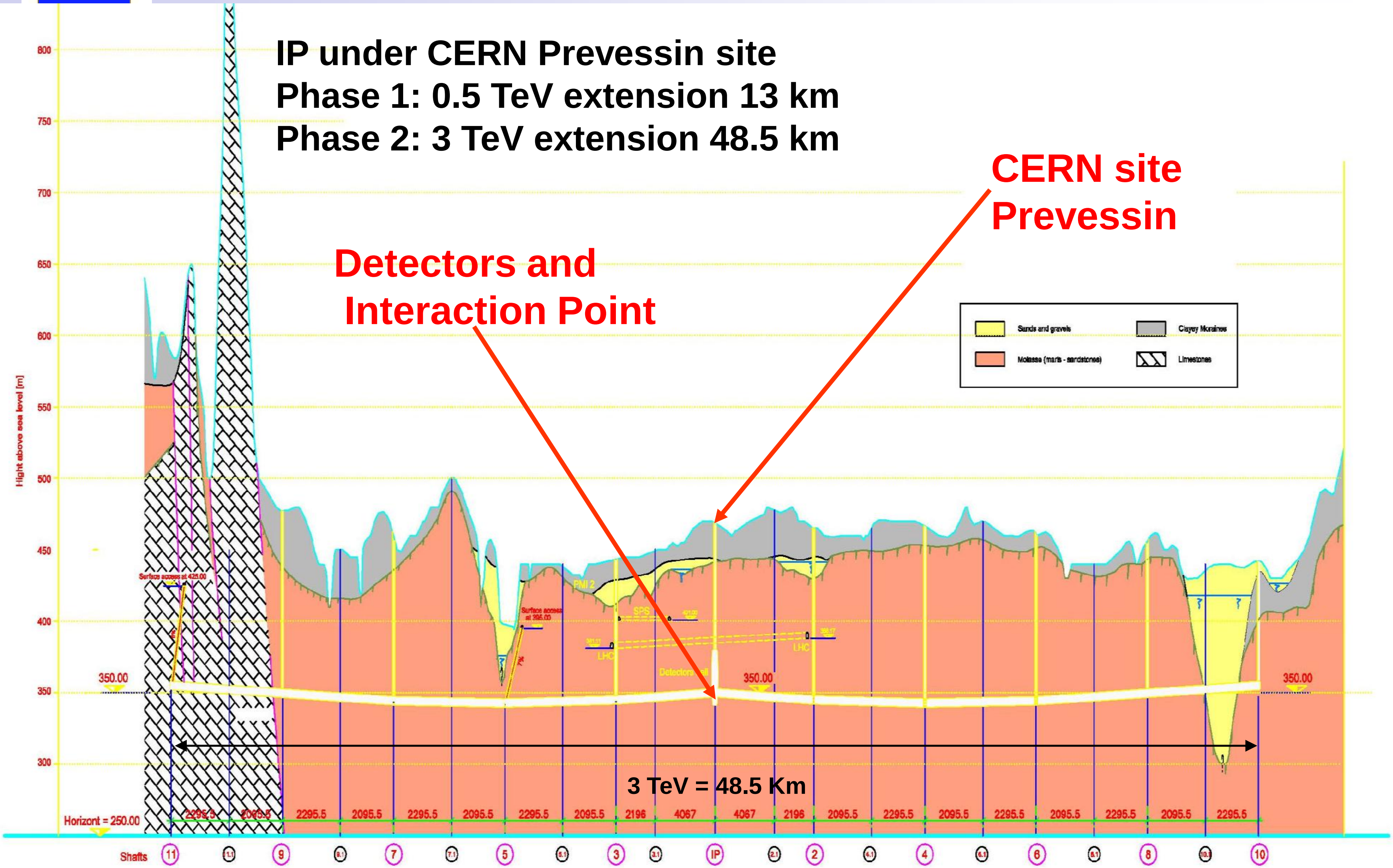


3 TeV

Laser Compton ring configuration

3 TeV CLIC at CERN

IP under CERN Prevessin site
Phase 1: 0.5 TeV extension 13 km
Phase 2: 3 TeV extension 48.5 km



CLIC Major Accelerator Challenges

- **Main beam acceleration**
  - Factors vs "state of the art": accel. gradient ~x2 , with break-down rate ~x1/30 (even after switch from 30GHz to 12 GHz)
- **Totally new RF power scheme**
  - 2-beam acceleration needs powerful and STABLE low energy beam (phase stability and uniformity of the pulse current)
- **Unexplored beam dynamics regimes**
  - 50 times smaller 4D emittance from Damping Rings than ever achieved
  - 1 nm tolerances on magnet vibrations in main linac, 1 A in IR
  - 1 nm vertical beam size (x70 smaller than ever achieved in LC)
- **Enormous number of elements** (>200,000)
- **Hard to demonstrate feasibility of one unit:**
  - ~900 m or 90 GeV (compare eg with ~1 GeV for ILC RF unit)
  - drive beam source needs (multi)B$ investment

Complexity of Colliders

	LHC	MC	CLIC
state of the art magnets	√	√	-
state of the art RF system	-	√	√
state of the art beam dynamics	-	√	√
Total # of elements	~4,000	~4,000	~200,000
Luminosity	>1e34	>1e34	>1e34

Did the Challenges and Complexity Scare CERN?

Not at all:

- **Each problem, taken separately, can be solved**
  - There are several approaches to each (RF, PETS, Dynamics, BDS)
  - Each must be addressed → needs time, $$, people
- **"Chicken or Egg?" - "People or Money?"**
  - People: they formed a core at CERN and then attracted many from Europe, and, later, Japan, US and ILC
  - core group (~1/3 of headcount) does ~2/3 of the work (highest priority)
- **That required 3 things:**
  - courage
  - ability to set a path and follow
  - strong back up of the lab

World-wide CLIC / CTF3 collaboration

27 collaborating institutes

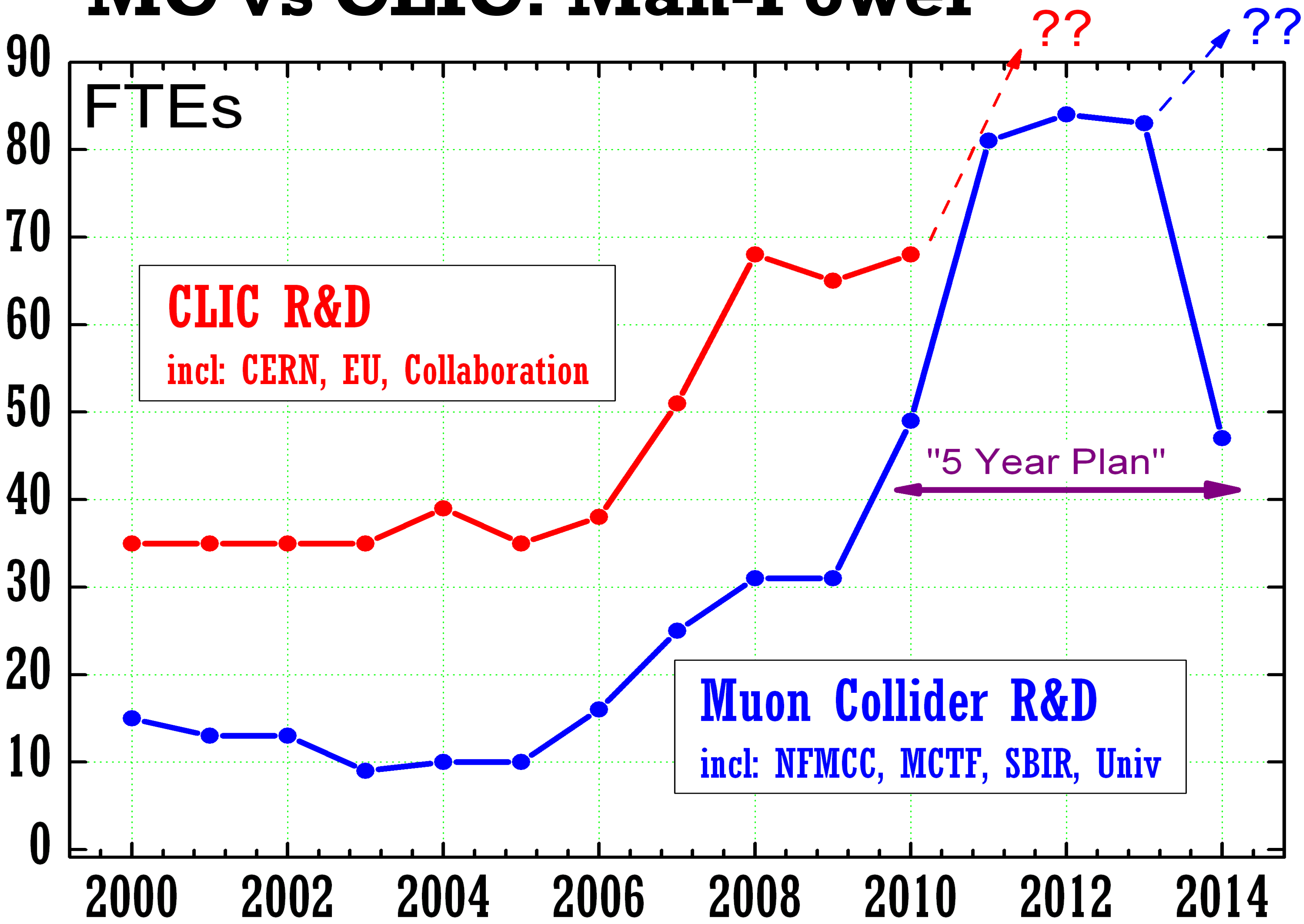
Ankara University (Turkey)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)
IRFU/Saclay (France)

Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
Instituto de Fisica Corpuscular (Spain)
INFN / LNF (Italy)
J.Adams Institute, (UK)

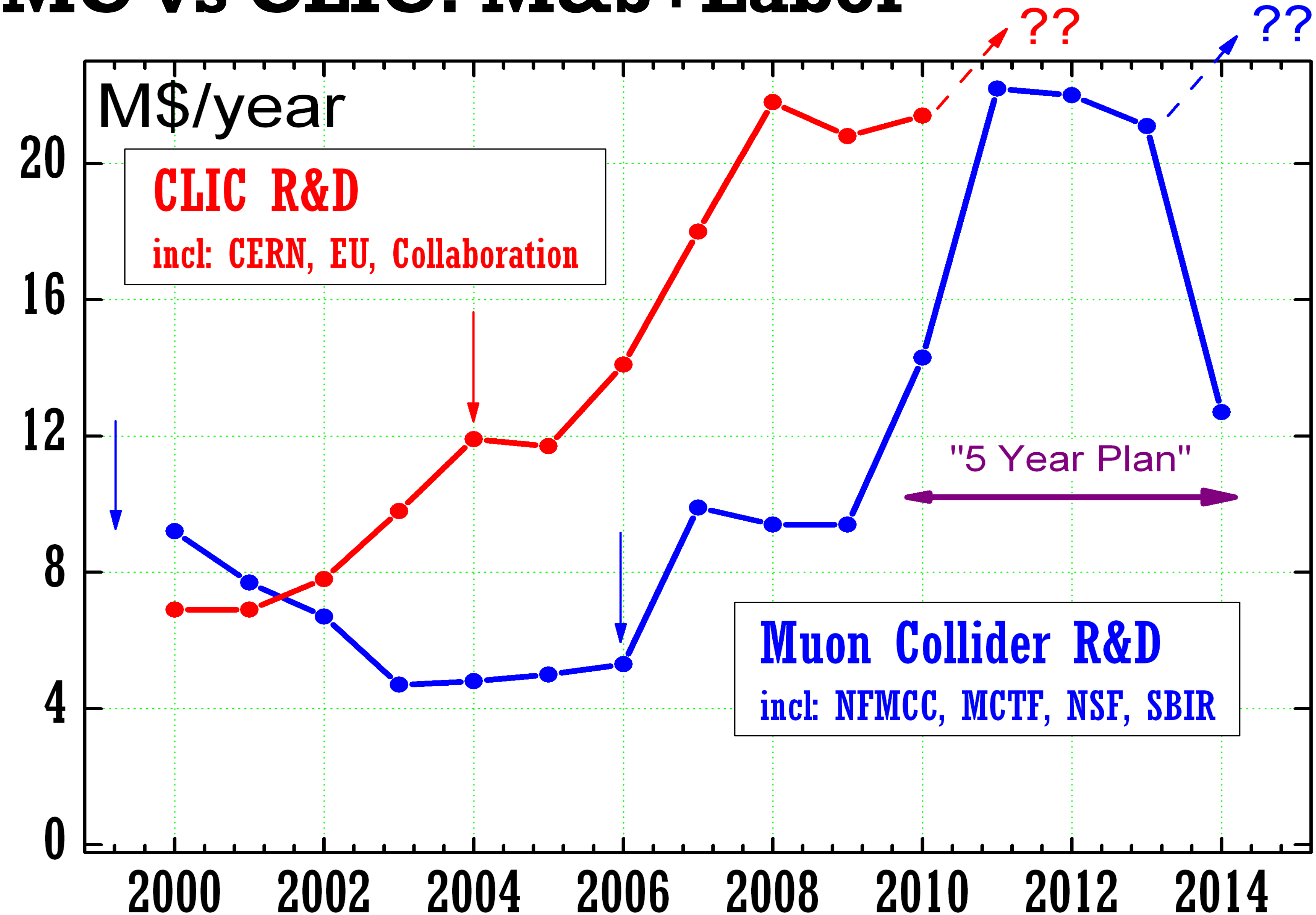
JINR (Russia)
JLAB (USA)
KEK (Japan)
LAL/Orsay (France)
LAPP/ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)

University of Oslo (Norway)
PSI (Switzerland),
Polytech. University of Catalonia (Spain)
RRCAT-Indore (India)
Royal Holloway, Univ. London, (UK)
SLAC (USA)
Uppsala University (Sweden)

MC vs CLIC: Man-Power



MC vs CLIC: M&S+Labor



Focus on Technology → Applications Will Come

- **CLIC two-beam technology:**
  - Initial justification for 250 GeV LC
  - Then 0.5TeV
  - Then 3 TeV
  - Then e-p collider LeHC= LHC +LC
  - … will find the best use when the dust settles
- **What is it for Muon Colliders**
  - High luminosity High energy (> 1 e34 and 3-10 TeV CoM)
  - High Energy Low Luminosity (~1e31, 1TeV or Z'-factory)
  - Low Energy Low Luminosity (Higgs-factory, >1e30)
  - Neutrino Factory: High Energy or Low Energy

Luminosity Scaling

- Peak Luminosity :

$$L = \frac{f_{collisions} \, N_b \, N_{\mu^+} N_{\mu^-}}{4\pi\sigma_\perp^{\,2}} H\left(\sigma_l / \beta^*\right)$$

- Introduce emittances:

$$\varepsilon_n = \gamma\sigma_\perp\vartheta_\perp = {\gamma\sigma_\perp^{\,2}}\Big/{\beta^*} \quad \text{so } \sigma_\perp^{\,2} = {\varepsilon_n\beta^*}\Big/{\gamma}$$

$$\varepsilon_l = \gamma\sigma_l \frac{\delta E}{E} = \gamma\sigma_l^{\,2} F_{RF} \text{ so } \beta^* \approx \sigma_l \propto \left(\frac{\varepsilon_l}{\gamma^{1/2}}\right)^{1/2}$$

Luminosity Scaling

- Average Luminosity :

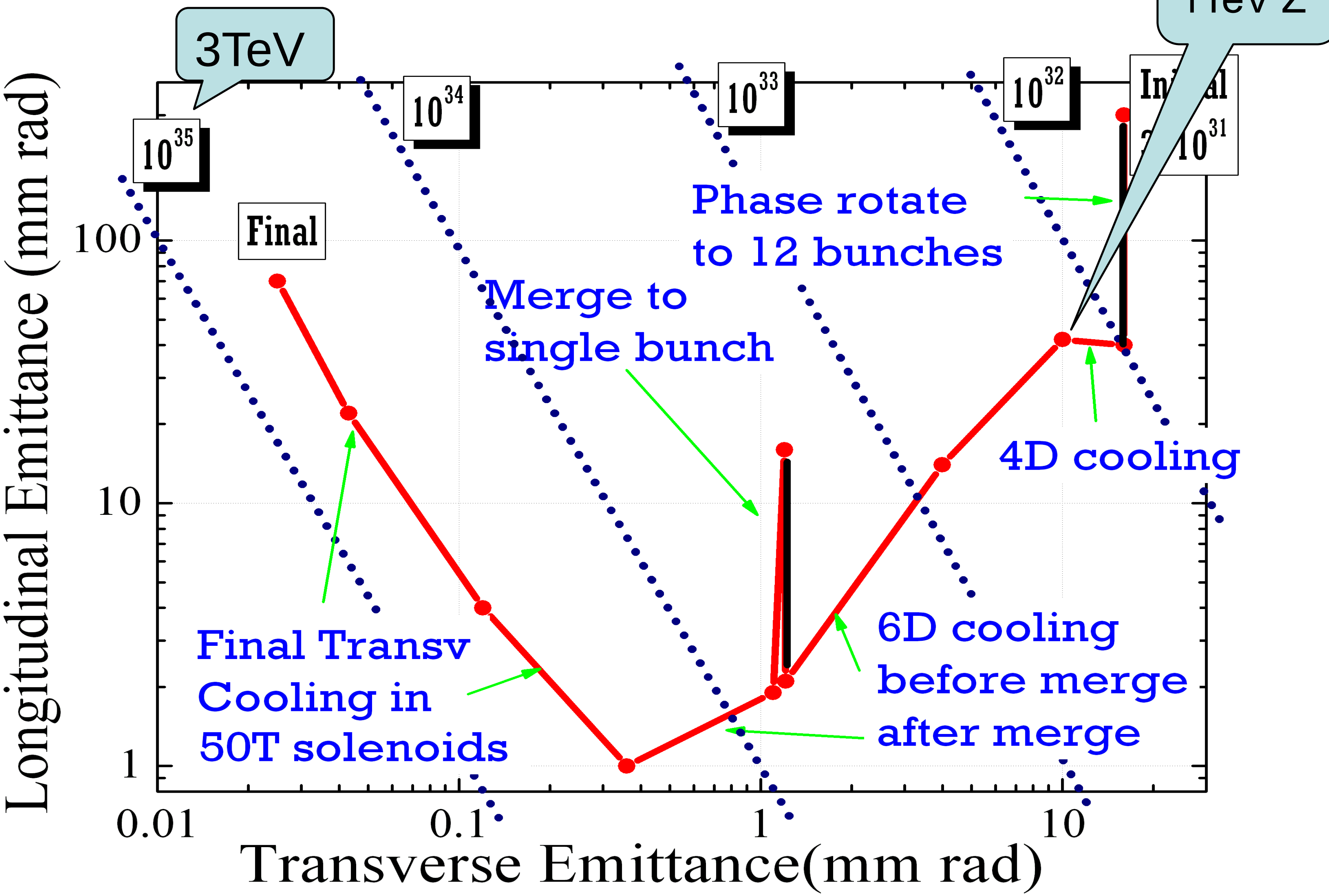
$$< L > \propto \left(f_{rep} n_{turns} \right) \cdot \frac{1}{\sqrt{\varepsilon_{6D}}} \cdot \frac{\left(N_b N_\mu \right)^2}{N_b} \cdot \gamma^{5/4}$$

- Where 6D emittance and lifetime:

$$\varepsilon_{6D} = \varepsilon_x \varepsilon_y \varepsilon_l = \varepsilon_n^2 \varepsilon_l$$

$$n_{turns} \approx 1000 \cdot (B / 5T)$$

Luminosity vs Cooling



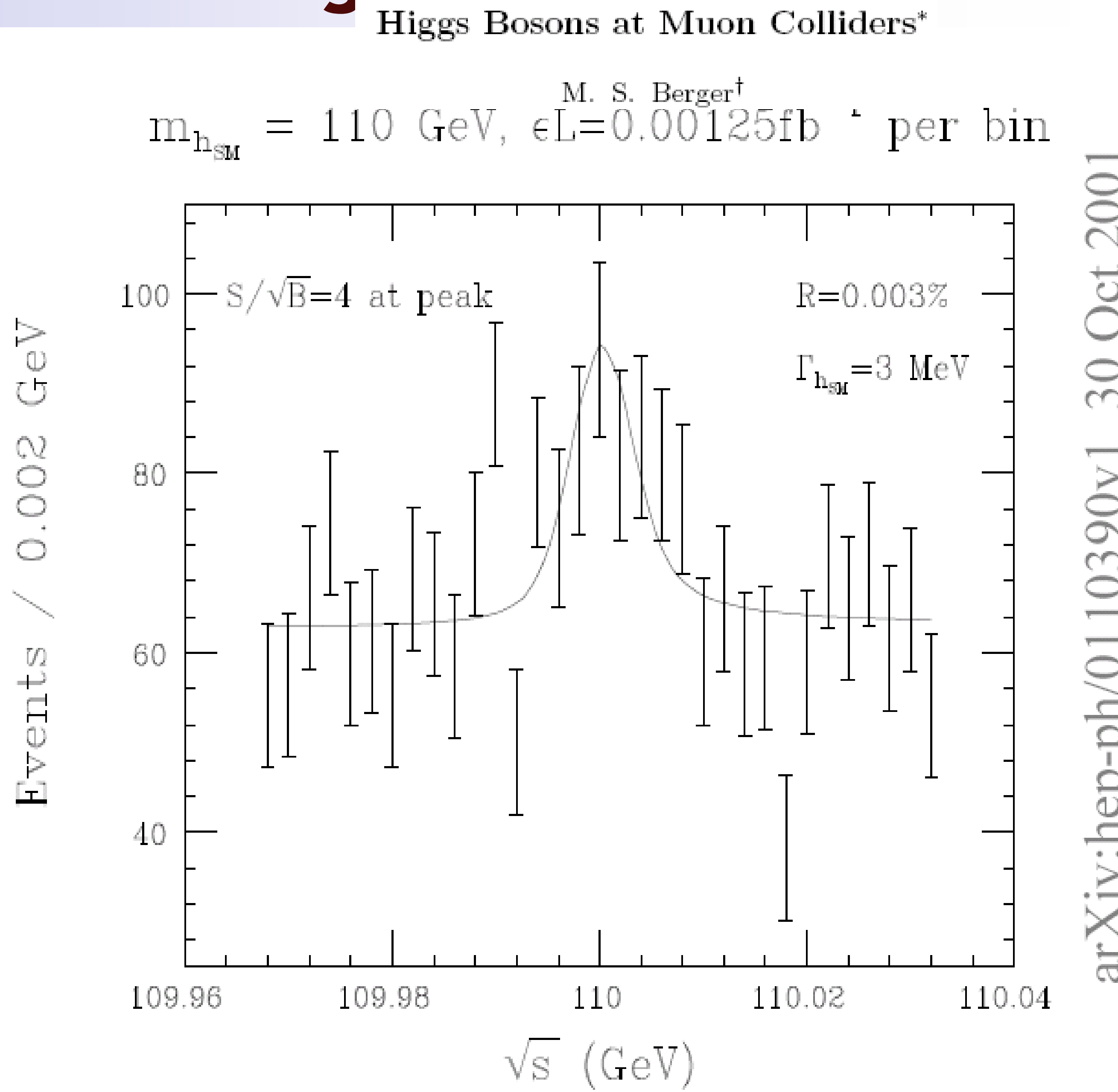
Superb Energy Resolution

1999 MC Study showed that dE/E~0.003% possible :

Deep long.cooling

Low luminosity

Need restart serious consideration of MC Physics options → "MC Physics and Detector Workshop" ~12/09



So the Answers Are :

High Energy Muon Collider:

Is It Right Machine For US?

Yes (back to Energy Frontier, small)

Are These Guys Serious?

Very much so (…and smart)

When Will We Know It Is Feasible?

Depends… may be even now - ?

Focus on technology development

Support 5 year plan=chance to be in the game